Impact of teak and eucalypt monoculture on soils in the highlands of Kerala

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Cochin University of Science and Technology
in partial fulfillment of the
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Doctor of Philosophy
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Under the Faculty of Environmental Studies

by

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CERTIFICATE

This is to certify that the research work presented in this thesis entitled **Impact of teak and eucalypt monoculture on soils in the highlands of Kerala** is an authentic record of the research work carried out by Ms. T. Geetha under my supervision and guidance in the Soil Science Discipline, Kerala Forest Research Institute, Peechi, in partial fulfillment of the requirements for the degree of Doctor of Philosophy and that no part of this work has previously formed the basis for the award of any degree, diploma, fellowship or associateship or any other similar title or recognition .

Peechi
08 January, 2008

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DECLARATION

I do hereby declare that the work presented in this thesis entitled ***Impact of teak and eucalypt monoculture on soils in the highlands of Kerala*** is an authentic record of the research work carried out by me under the guidance and supervision of Dr. M. Balagopalan, Programme Coordinator, Instrumentation Division and Scientist-in-Charge (F), Soil Science discipline, Kerala Forest Research Institute, Peechi, and no part of this has previously formed the basis for the award of any degree, diploma, associateship, fellowship or any other similar title or recognition.

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Introduction

1.1. General introduction

Forests of a country are natural assets of enormous value. An adequate extent of forest, if ideally dispersed, scientifically managed, and judiciously utilized is a perpetual renewable natural resource that confers immense benefit, both directly and indirectly on the population. From the earliest times, teak - the Golden timber - was extracted from the forests. The advent of British in India led to a period of intensive forest exploitation wherein large number of trees were felled indiscriminately. During World War I and II, forest resources were severely depleted as large quantities of timber were removed to build ships and railway sleepers and to pay for Britain's war efforts.

The idea of conservation first entered the list of colonial concerns as a consequence of the unrest over the possibility of ultimate drying up of crucial teak supply. Consequently attempts were made to raise plantations of teak. Mr. H. V. Conolly, the then District Collector of Malabar, initiated the first ever attempt to raise teak plantations. The first ever teak plantation in India, and also possibly in the world, was raised in Nilambur in 1842 which marked the beginning of monoculture in the South Indian forests. Large extent of moist deciduous forests was subsequently converted to monoculture teak plantations.

At present, forest plantations accounting for 130 million ha. is approximately 3 per cent by area of world's forests. Out of these, just over half is located in the tropics. The global plantation resource is currently meeting about 35 per cent of demand of wood and this is expected to rise to 46 per cent by 2040 (Allan and Lanly, 1991; FAO, 1995; Trevor *et al.*, 2001).

Today, teak ranks third among tropical hardwood species in terms of plantation area established world-wide, covering 2.25 million ha, with 94 per cent in Tropical Asia, major area being in India and Indonesia. About 4.5 per cent of teak plantations are in tropical Africa and the rest are in tropical America (Krishnapillay, 2000; Katwal, 2003). In Kerala, teak is the major plantation species occupying an area of 57,855 ha. covering more than 50 per cent of forest plantation area and 2 per cent of the total geographic area (Nagesh Prabhu, 2003)

Eucalypt was first introduced in India at the Nandi hills in 1790 as garden trees with 16 species (Shyam Sunder, 1986). Later, one of the species - *Eucalyptus globulus* (blue gum), was cultivated in the Nilgiris in 1843 by Captain Cotton of the Madras Regiment to create a fuel resource in the Nilgiri plateau (Kondas and Venkateshan, 1986). About one million hectare of land is under eucalypt cultivation by Forest Departments and Forest Development Corporations in India (Varghese *et al.*, 2001).

At present, plantations of eucalypts in India supply pulpwood to pulp and paper industries. Bamboo and reeds were the conventional raw materials for the pulp and paper industry in Kerala. Large scale conversion of moist deciduous forests to plantations for economic gain and the construction of major hydel and irrigation projects inside the forests have led to the depletion of bamboo and reeds. Competing demand by traditional industry has also reduced their availability to pulp and paper industries. To meet the ever-growing demand, it was found necessary to have fast growing species, which can yield higher pulpwood per unit area. For this purpose, eucalypt was found to be the best choice.

Of the 600 species of eucalypts in Australia, two species viz. *E. grandis and E. tereticornis* have performed well in Kerala (Chand Basha, 1986). Kerala Forest Department commenced large scale planting of *E. grandis* in the late 1950s as an afforestation scheme in the high ranges in Peerumade, Pampa and Devikulam. Today, plantations of eucalypt cover 40,000 ha. (Sankaran *et al.*, 1999).

Plantations can have three main impacts on soils

1. nutrient removal from the soil as tree grows and are then harvested,
2. changes in the chemistry of soil surface as the litter layer and organic matter are dominated by one species and hence uniform composition and decay characteristics and,
3. site preparation practices which directly affects soil physical parameters and in turn nutrient and moisture availability (Evans, 2000).

Changes in soil properties in turn affect the productivity and sustainability of plantations. Thus, studies of soils in plantations are of utmost importance. The available literature on these aspects is, herewith, reviewed.

1.2. Review of literature

1.2.1. Soils and vegetation types

In forest ecosystem, trees affect soil properties through several pathways. Trees alter inputs to the soil system by increasing capture of wet fall and dry fall and by adding to soil nitrogen via nitrogen fixation. They affect the morphology and chemical conditions of the soil as a result of the characteristics of above- and below-ground litter inputs. The chemical and physical nature of leaf, bark, branch and roots alter decomposition and nutrient availability via controls on soil water and the soil fauna involved in litter breakdown. Extensive lateral root systems scavenge soil nutrients and redistribute them beneath tree canopies. In general, trees represent both conduits through which nutrients cycle and sites for the accumulation of nutrients within a landscape. Understanding species-specific differences in tree-soil interactions has important and immediate interest to those concerned with maintaining or increasing site productivity (Rhoades, 1996). Soils in turn can also influence vegetation types. By and large, it is the soil depth, moisture regime, porosity, aeration and availability of nutrients that determine the vegetation types on a particular soil (Gama *et al.*, 1999).

Studies on surface soils with similar parent materials, ground cover and topography but with different vegetation types found that the most notable differences between the sites were in organic carbon (Singh *et al.*, 1988). It was observed that carbohydrates varied under different tree species over different parent materials and under similar climatic conditions, in forest soils of outer Himalayas (Singh and Singhal, 1974).

1.2.2. Soils in plantations of different species

In Kerala, with few exceptions, conversion of natural forests for raising plantations, mostly monocultures, has been a common practice since 1960s. Biological uniformity of monoculture plantations has led to anxieties that soil deterioration and consequent reduction in site quality may result, following their wide spread adoption. The basic underlying reasons for these are fragility of top soil structures, the disturbances to decomposer activity when mixed forest litter is replaced by uniform plantation litter, the repeated exposure of the soil to sun and rain, the removal of organic matter and nutrients in harvest, and the effect of associated management practices (Balagopalan and Jose, 1997).

1.2.2.1. Physical properties

On studying the changes following the replacement of tropical rain forest with high value plantation crops in South Andaman and Little Andaman islands, Mongia and Bandyopadhyay (1992a) observed lower profile water content, water storage, water intake rate and bulk density under plantations when compared with virgin forest. Increased bulk density in the areas cleared for commercial plantations and agricultural use in the Andaman and Nicobar Islands was also reported by Dagar *et al.* (1995). They also observed that water storage within 180cm soil depth was maximum in evergreen forests and minimum in teak and was found to be significantly correlated with organic matter content. It was concluded that water balance was negatively affected by the monoculture of commercial plantations.

Balagopalan (1995b) studied the soil characteristics in natural forests (evergreen and moist deciduous forests), grassland, and plantations of teak and cashew in the Malayattoor Forest Division, Kerala. Excluding gravel and silt, most properties differed significantly due to vegetation types. Soils in the plantations were found to be deteriorated when compared to those in natural forests.

Detrimental effects on soil physical properties - increased bulk density and decreased soil moisture content - was also reported by Joshi *et al.* (1997) in soils of 1-8 year old plantations of *Populus deltoids* when compared to natural forest in the low montane subtropical belt of the Kumaun Himalaya.

A study in 28-year-old even-aged contiguous monocultures, located in the lowland rain forest belt of southwestern Nigeria, consisting of teak, idigbo (*Terminalia ivorensis*), opepe (*Nauclea diderrichii*) and gmelina (*Gmelina arborea*) revealed that soil texture was not affected by plantation activities (Okoro *et al.*, 2000).

1.2.2.2. Chemical properties and macro nutrients

Lower organic matter, Bray's phosphorus and available potassium in plantation soils of teak, red oil palm, and padauk, compared to forest soils was reported by Mongia and Bandyopadhyay (1992a). Dagar *et al.* (1995) observed significant decreases in soil pH, organic matter, extractable phosphorus and exchangeable potassium contents in areas cleared for commercial plantation in the Andaman and Nicobar Islands. They also concluded that nutrient cycling was negatively affected by the monoculture of commercial plantations.

Balagopalan (1995a) studied the soil characteristics in natural forests (evergreen and moist deciduous forests), grassland, and plantations of teak and cashew in the Malayattoor Forest Division, Kerala. Excluding available phosphorus, calcium and magnesium, all other properties differed significantly due to vegetation types. Soils in the plantations were found to be deteriorated when compared to those in natural forests.

The soils in plantations and adjacent natural forest stands in highland Ethiopia were studied by Michelsen *et al.* (1996) and concluded that the overall soil characteristics of the natural forests differed from those of the five most common plantation tree species. They observed that the natural forest soils had higher contents of total nitrogen, available phosphorus and exchangeable calcium. This was attributed to

a. loss of organic matter during conversion of natural forests to plantations
b. increased leaching in young plantations, and
c. low nutrient demand by natural forest trees as compared with fast-growing exotics.

Joshi *et al.* (1997), on studying the soils in 1-8-year-old plantations of *Populus deltoides*, and nearby natural forest in the low montane subtropical belt of the Kumaun Himalaya reported that soil organic carbon, nitrogen, phosphorus and potassium decreased with increasing plantation age. A study by Lian and Zhang (1998) in China demonstrated that natural broadleaved evergreen forest has a greater capability of nutrient return, coupled with higher rates of litter decomposition and nutrient release, larger soil nutrient pools, and higher nutrient availability than pure plantations.

A study in 28-year-old even-aged contiguous monocultures, located in the lowland rain forest belt of southwestern Nigeria, consisting of teak, idigbo (*Terminalia ivorensis*), opepe (*Nauclea diderrichii*) and gmelina (*Gmelina arborea*) revealed significant losses in soil calcium and available phosphorus (Okoro *et al.*, 2000). However, the effective cation exchange capacity, pH and magnesium contents of the soils were not affected by plantation activities. The soil organic carbon content was also found to be not affected. Significant variation of some of the properties with depth was observed for plantation soils.

Aweto (2001) observed that the rates of nutrient uptake and recycling varied with tree species and ecological zones in West Africa. He evaluated the impact of monoculture plantations on nutrient cycling and concluded that the plantations immobilized soil nutrients faster and returned less nutrients to the soil than native forest and savanna vegetation, thus depleting soil nutrients. Owing to their effects in destabilizing the nutrient cycle in forest and savanna ecosystems, planting monocultures of fast-growing tree species are not likely to be sustainable in the long-term. The widespread adoption of plantation forestry as an alternative to the natural regeneration of native forests as a strategy for increasing the wood resources of humid tropics is, therefore, indicative of an uncritical acceptance of the view that monoculture tree plantations are sustainable.

Differences in nitrogen, phosphorus, potassium and organic carbon contents were observed due to plantation activities of sal, teak, eucalypt and pine at Forest Research Institute, Dehra Dun (Pande, 2004). The available per cent of nutrients (phosphorus, potassium, calcium and magnesium) were highest in eucalypt and lowest in sal, while teak followed pine. The order of importance for nitrogen was: teak>sal>eucalypt>pine and for organic carbon, it was teak>eucalypt>sal>pine. These soil nutrient variations were related to litter fall and subsequent decomposition.

The results of the study by Guo -Jian Fen *et al.* (2004) demonstrated that the natural forest has a greater carbon return through litterfall than monoculture plantations, which is beneficial to the increase of soil organic matter storage and the maintenance of soil fertility.

Xu-DaPing and Dell-Ber Nie (2002) stated that that the productivity of well-managed plantations can be sustained whereas poor management practices result in dramatic yield declines across rotations and continued soil degradation. The mixed stand of forest species seemed to be the best plantation system, as it increased soil organic matter and fertility level and improved soil structure.

1.2.2.3. Organic matter fractions

It was observed that the composition of organic matter in soil changes under monoculture. Wang (1967) reported that in soils of coffee plantations, 50 per cent of organic matter is composed of fats and waxes.

1.2.3. Soils in teak plantations

1.2.3.1. Physical properties

The earliest study on soils in teak plantations and adjacent natural forests showed no substantial difference in the distribution of particle-size separates. However soils in plantations were found to be much harder due to exposure (Champion, 1932). Teak cropping led to soil erosion, especially due to the removal of undergrowth. Laurie and Griffith (1942) also observed increased soil erosion in teak plantations especially when undergrowth and litter are burned. Bell (1973) found soil erosion 2.5 to 9 times higher in plantations than in under natural forest.

When the morphological and physical properties of soils of teak plantations of different age were studied, an increase in compaction was noticed in the older teak plantations (Jose and Koshi. 1972). Increased compaction in younger teak plantations (11 years) was also observed by Rathod and Devar (2003a). They also observed a change in texture from loamy sand to sandy loam in young plantations of teak.

Aborisade and Aweto (1990) studied the effects of exotic tree plantations of teak and Gmelina on a forest soil in South-western Nigeria and found that the soil was significantly denser in the 0-10cm layer of forest soil. Ram and Patel (1992) studied infiltration capacity of compacted soils under a 21-year-old teak plantation and forest floor in West Bengal. They found that the bulk density increased, and porosity, initial infiltration rate (first 5 minutes) and accumulated infiltration depth (elapsed time 180 minutes) decreased in plantation soils when compared to natural forest. The intake of water under compacted conditions was less than one third of that of a normal forest floor after a time lapse of 180 minutes. The plantation soils had undergone compaction due to excessive biotic interference.

Balagopalan *et al.* (1992) studied the physical properties of soils in monocultures of teak (*T. grandis*) and eucalypt (*E. tereticornis*, uncoppiced and coppiced), and mixed stands of teak and bombax (*Bombax ceiba [B. malabaricum]*) in Thrissur Forest Division, Kerala. They found that the differences in physical properties were negligible. Chavan *et al.* (1995) studied the effect of forest tree species *viz.*, *T. grandis, Terminalia tomentosa, Pongamia pinnata, G. arborea,* eucalypt, *Acacia auriculiformis, and Casuarina equisetifolia* on properties of lateritic soil [Maharashtra] and concluded that there was no change in soil physical properties.

Okoro *et al.* (1999), on comparing the soil physical properties of some monoculture plantations (*T. grandis, T. ivorensis, Nauclea diderrichii* and *G. arborea*) in the lowland rain forest belt of South-western Nigeria with that of natural forest found that the texture of the soils were not affected by the respective plantation species. Amponsah and Meyer (2000) studied soils of natural forests converted to teak plantations (21.3 ± 5.1 years) in the Offinso and Juaso Forest Districts in the Ashanti region, Ghana and found that in the 0-20cm and 20-40cm depth, bulk density significantly increased.

1.2.3.2. Chemical properties

The initial study on soils in teak plantations and adjacent natural forests showed no substantial difference in the chemical properties (Champion, 1932). The problem noticed was rapid laterization associated with teak cultivation (Davis, 1940). Griffith and Gupta (1948) were of the opinion that laterization is of geological duration, and that it is a primary process of weathering down of the parent geological rock to a laterite type. The probable change taking place in the soil mass, after clear-felling and planting, might be hardening of the laterite or the lateritic soil, in case the latter pre-existed in the locality, and not its formation as suggested by some workers. Gupta (1956) also found little change in the chemical nature of the soils in teak plantations, in particular, the SiO_2/R_2O_3 ratio, which is the index of laterization of soil.

The fear that monoculture teak plantations may lead to soil deterioration and consequent reduction in site quality have led to a large number of studies on nutrient distribution, litter production, its decomposition and its effects on soil. Chaubey *et al.* (1988) found that litter production was 1.5-2.0 times greater in the teak plantations (20-23 year) than in adjoining forest. Greater contents of nitrogen, phosphorus, potassium and calcium were noticed in plantations than in forest litter, indicating a greater nutrient return in the plantations. Annual leaf litterfall was higher in teak than in eucalypt (Singh *et al.*, 1993). It was also observed that decay rate of the litter varied significantly both in the field and in the laboratory. Teak litter decomposed rapidly when compared to that of *E. tereticornis* (Singh *et al.*, 1993; Pande and Sharma, 1993a; Sankaran, 1993; Maharudrappa *et al.*, 2000; Panda and Swain, 2002). Exchangeable calcium and magnesium were highest in soils incorporated with eucalypt leaf litter than soils with teak (Maharudrappa *et al.*, 2000).

When the chemical properties of soils in teak plantations of different age were studied, a decrease in soil fertility was noticed in the older teak plantations (Jose and Koshi, 1972). Similar observation on decline in soil fertility in successive rotation teak plantations in Kerala was also noted by Balagopalan and Jose (1982a). Alexander *et al.* (1981) found that some of the soil properties showed a tendency to change in second rotation when compared to first. Balagopalan and Jose (1982a) observed a decrease in soil organic carbon content and total nitrogen in second rotation when compared to the first. A decline in soil organic carbon distribution in teak plantations when compared to natural forests was also reported by Balagopalan and Alexander (1984).

Aborisade and Aweto (1990) studied the effects of exotic tree plantations of teak and Gmelina on a forest soil in South-western Nigeria and found that the concentrations of total nitrogen, exchangeable calcium, magnesium and potassium were greater under forest soil, but the concentrations of available phosphorus were similar under all three ecosystems.

Balagopalan *et al.* (1992) found that chemical properties of soils under monocultures of teak (*T. grandis*), eucalypt (*E. tereticornis*, uncoppiced and coppiced), and mixed stands of teak and bombax (*B. ceiba [B. malabaricum]*) in Kerala differed between plantations. Relatively low values for pH, organic carbon, exchangeable bases and exchange acidity were observed in monoculture teak and eucalypt (uncoppiced and coppiced) compared to those in mixed plantations.

Marquez *et al.* (1993) studied the effect of a teak chronosequence (in 2-, 7- and 12- year old plantations) on soil properties in the Ticoporo Forest Reserve, Venezuela. Calcium and magnesium contents, pH and cation exchange capacity were significantly higher in the soils of the 12-year-old plantation than in the younger plantations. The available soil phosphorus concentration showed a significant decline with plantation age, while potassium content showed little variation. They suggested the possibility that older teak trees could take nutrients more efficiently from deeper soil horizons and return them to the soil surface as leaf litter. The increase in soil nutrients observed could be a consequence of leaf litter decomposition and further nutrient cycling. Pande and Sharma (1993b) noted teak and sal conserved more nutrients than pine and eucalypt, and conservation of nitrogen and phosphorus was greater than that of other nutrients.

Mongia and Bandyopadhyay (1994) measured soil properties under natural and mature plantations in South Andaman, India. Soil nitrogen, phosphorus, potassium, organic carbon and pH were lower under teak, red oil palm (*Elaeis* spp.), padauk and rubber plantations than in natural forests. Litter production of teak plantations was nearly 53-59 per cent of that produced in natural forest and soil nutrient contents were correspondingly lower. Chavan *et al.* (1995) studied the effect of forest tree species *viz.*, *T. grandis*, *T.tomentosa*, *Pongamia pinnata*, *G. arborea*, eucalypt, *A. auriculiformis*, and *Casuarina equisetifolia* on properties of lateritic soils in Maharashtra and concluded that there were marked effects on the soil chemical properties compared with natural forest soils. Organic carbon, available nitrogen, phosphorus and potassium increased significantly in the surface layer. The cation exchange capacity and exchangeable cations also increased due to the decomposition of organic matter added through leaf litter. In general, the soils under the forest cover showed higher nutrient status.

Salifu and Meyer (1998) evaluated the physico-chemical properties of soils associated with logged forest and areas converted to teak in Ghana and found significantly higher nitrogen and magnesium concentrations and organic matter contents in the surface soil horizons under logged forest than in teak plantations. Phosphorus and potassium concentrations were also significantly higher in logged forest. In B-horizons, higher calcium content in soils of teak plantations was attributed to the active role of teak in pedogenesis. Higher calcium content in soils of teak was also observed by Rathod and Devar (2003b). This may be due to the higher content of calcium in teak leaf litter.

Okoro *et al.* (1999), on comparing the soil chemical properties of some monoculture plantations (*T. grandis*, *T. ivorensis*, *Nauclea diderrichii* and *G. arborea*) in the lowland rain forest belt of South-western Nigeria with that of natural forest found that the conversion of the natural tropical forest to monoculture species resulted in significant loss of soil calcium and available phosphorus. However, the effective cation exchange capacity, pH and magnesium content of the soils were not affected by the respective plantation species. The soil organic carbon content was similarly not affected. A study by Suwannaratana (1999) in 6, 32, and 50 year old teak plantations, a degraded teak forest and a natural teak forest in Thailand recorded highest organic carbon content in the natural teak forest and the lowest level in the 50 year old teak plantation (3.65 and 1.96 per cent, respectively).

Amponsah and Meyer (2000) studied soils of natural forests converted to teak plantations (21.3 ± 5.1 years) in Ghana and found that in the 0-20cm depths, soil organic matter content, total nitrogen, available phosphorus, and exchangeable potassium, calcium and magnesium significantly decreased in soils where natural forests were replaced with teak plantations. Similar results were found for the 20-40cm soil depths.

Chamshama *et al.* (2000) compared chemical properties of soils under first rotation teak and natural forests at Tanzania. The soil pH and exchangeable cations from the teak plantations were not significantly different from those of the natural forests. The soil EC within 0-70cm depth in the young plantations decreased by 24 per cent while in the semi-mature plantations, it increased by 36 per cent, compared with the adjoining natural forests. In general, there was a decrease in total nitrogen in the young plantations but an increase in the semi-mature plantations. In both young and semi-mature stands, there was a decrease in available phosphorus.

1.2.3.3. Micro nutrients

Comparative study on soil micronutrient status in natural forest and teak plantations are rare although few woks on micronutrient status of forest soils are available. Karia and Kiran (2004) found that the soil micronutrient content of closed teak forest, closed mixed forest, open mixed forest, degraded forest and scrub in Gujarat was good. Micronutrient status in a dry deciduous tropical forest and scrub jungle of Mettupalayam was recorded by Thiyageshwari *et al.* (2006). Jianwei Li *et al.* (2006) observed that manganese and zinc in soils were depleted following the growth of a forest from seedling stage up to thirty five years. They also observed that contrasting processes control the bio-availability of copper, zinc, manganese and iron in soils. Dhanya *et al.* (2006) compared the micronutrient content of I^{st} , II^{nd}, III^{rd} rotation plantations of comparable age and came to the conclusion that zinc content in plantation soils decreased significantly with rotation.

1.2.3.4. Organic matter fractions

Replacement of natural forest with plantations of teak changes both the content and nature of organic matter in soils. Balagopalan (1991) reported significant difference in proximate constituents of organic matter in plantations and natural forest.

1.1.4. Soils in eucalypt plantations

The major limitations of tropical soils for short rotation tree crops are low nutrient reserves and poor nutrient retention ability (Tiarks *et al.*, 1998). Short rotation results in long term decline in soil organic carbon content, probably due to more frequent plantation activities and disruption to the flow of carbon to the soil through litter (Polglase *et al.*, 2000; O'Brien *et al.*, 2003).

1.2.4.1. Physical properties

Balagopalan (1987) observed increased gravel content and bulk density in plantations of eucalypt when compared to natural forest. Soils in *E. tereticornis* were found to have greater accumulation of gravel and lower water holding capacity than those in the natural forest in Thrissur, Kerala (Balagopalan and Jose, 1993). On comparing the properties of the top 30cm soil under plantations of 1- to 8- year old *E. tereticornis* and adjacent natural mixed broadleaved forest in the subtropical zone of the central Himalaya, Bargali *et al.* (1993) noted that several soil physical properties (water holding capacity, porosity and water content) decreased with increasing age, while bulk density increased. A significant coarsening of texture and increase in bulk density was observed in *E. camaldulensis* plantations than under natural vegetation in Nigeria (Jaiyeoba, 1995). Balagopalan and Jose (1997) studied the effect of teak, eucalypt and rubber on soils in Thrissur, Kerala and came to the conclusion that soils under eucalypt plantations were highly compacted and had lower fine fractions than those of natural forest.

1.2.4.2. Chemical properties and macro nutrients

On comparing soils in 18-20Y old *E. tereticornis* plantation with that of 44-54 year old *T. grandis* plantation, Singh *et al.* (1990) noted that organic carbon, total nitrogen, available potassium, exchangeable magnesium and cation exchange capacity were highest in eucalypt while exchangeable calcium was higher in *T. grandis* plantations. Bargali and Singh (1991) studied biomass, productivity, nutrient status and nutrient cycling in 8 year old *E. tereticornis* plantation and Natural Sal forest in Uttar Pradesh and found that the net nutrient uptake of *E. tereticornis* was lower than that of natural forest. They also concluded that this low nutrient demand will lead to lower nutrient cycling and poor nutrient availability in future years, as any available nitrogen in excess of uptake is likely to be lost by leaching or denitrification.

Sunita and Uma (1993) observed that organic carbon, nitrogen, phosphorus and potassium contents of soils in 3-, 6-, and 9 year old plantations of *E. tereticornis* is lower than that of natural forest. On comparing the properties of the top 30cm of soil under plantations of 1- to 8 year old *E. tereticornis*, and the adjacent natural mixed broadleaved forest in the subtropical zone of the central Himalaya, Bargali *et al.* (1993) noted that soil chemical properties, notably organic carbon, total nitrogen, phosphorus and potassium, decreased as a result of reforestation with *E. tereticornis* and further decreased with increasing age of the plantation. Decline in soil fertility due to short rotation eucalypt plantation was also reported by Balagopalan (1992).

A comparative study on the properties of soils in relation to vegetation types led Balagopalan and Jose (1993) to conclude that soils in the natural forest have higher cation exchange capacity, organic carbon, nitrogen, P_2O_5, K_2O, CaO and MgO contents when compared to soils of natural forest. Lower nutrient concentration in soils of eucalypt plantations when compared to soils of natural forest was observed by Bargali and Singh (1995). They also noticed that concentration of nutrients was higher in soils of 25 year old eucalypt plantations than in 8 year old plantations. On comparing the soils of evergreen forest and adjacent eucalypt plantations, Balagopalan and Jose (1995) found that soils of eucalypt plantations had lower organic carbon, total nitrogen, cation exchange capacity and total phosphorus contents. Jha *et al.* (1996) studied soil nutrient changes under 5, 10, 15 and 20- year old eucalypt monocultures and natural sal forest in Uttar Pradesh. They concluded that soil nutrient depletion was highest in 10- and 15- year old eucalypt plantations than that in 5- and 20 year old eucalypt plantations. They attributed this pattern to faster mineralization of residual organic matter in five year old plantations and increase of soil nutrients with age in 20- year old plantation.

O' Connell *et al.* (1997) observed that, on poor sites common in the tropics, reduction in soil nutrient status and stand productivity are likely to occur. Substantial difference in nutrient cycling was noticed among species used in tropical plantation by Binkley *et al.* (1997). They observed that eucalypt return small amount of nutrients in litter fall compared to natural forest.

1.2.4.3. Micro nutrients

Micronutrient disorders, especially boron, copper, iron, manganese and zinc, have been recorded for eucalypt in nearly all the geographical regions where commercial plantations have been established. Whilst micronutrient disorders are often induced by the application of fertilizers containing only macronutrients, instances of primary boron deficiency in China and copper deficiency in Australia have been recently documented. Increasing records of micronutrient disorders in eucalypt plantations suggest that the capacity of micronutrient to limit productivity has not been adequately recognized in the past (Dell *et al.*, 2002)

On studying the effect of *E. camaldulensis* on soil properties and fertility, Baber *et al.* (2006) concluded that zinc, copper and iron decreased with distance from the tree in the surface soil while manganese increased. In plantations of eucalypt, available iron increased significantly with rotation. Higher iron availability in older eucalypt plantations than younger plantations was also reported by Sangha and Jalota (2005).

1.2.4.4. Organic matter fractions

A survey of literature pertaining to soil proximate constituents viz. fats and waxes, resins, free sugars, hemicellulose, cellulose, lignin-humus and protein indicates that these substances are probably the least studied of soil organic components. Soil organic matter chemists have largely ignored these materials in preference to studies on true humic materials, though they are known to affect many soil properties like aggregate stability, degree of wetting, solubility of soil nutrients and rate of decomposition and mineralization of soil organic matter. Organic matter fractions are also, in turn, affected by different soil properties. For example, pH affects the decomposition of fats, waxes and saccharides and adsorption of protein by kaolinite and montmorillonite. Decomposition of cellulose and hemicellulose is also influenced by soil properties like temperature, water content, aeration, nutrient availability etc (McLaren, 1954; Armstrong and Chesters, 1964; Greenland and Oades, 1975; Braids and Miller, 1975).

It has been reported that replacement of a natural forest by an exotic species brings about radical changes in the nature of organic matter. For example, replacement of Sal by eucalypt not only increased the content of carbohydrate in soils but also altered their nature (Singhal and Dev, 1977). Higher content of hemicelluloses and lower content of lignin, compared to sal, was also observed by Singhal and Sharma (1983).

1.3. Relevance and aims of the present study

Plantations are a significant component in terms of area and revenue of Kerala Forest Department. An area of about 57855 ha, which accounts for about 8.5 per cent of total forest cover and 50 per cent of area under plantations is currently under teak in Kerala (Nagesh Prabhu, 2003). The second major plantation crop of Kerala is eucalypt, which occupies 25 per cent of the plantation area. Thus, teak and eucalypt, together account for 75 per cent of plantation area in Kerala.

From the very beginning of plantation forestry, fear of soil deterioration in monoculture plantations was expressed. Numerous studies in plantation soils, especially soils in teak and eucalypt are available. However, a large number of these studies were attempts to correlate soil properties with decline in productivity of plantations and with rotation (Balagopalan and Jose, 1982a; Balagopalan and Alexander, 1984). Others compared soils in plantations with barren lands to assess the effect of afforestation (Jhorar *et al.*, 1993; Prathiban and Rai, 1994; Hosur and Dasog, 1995; Mapa, R. B., 1995).

Reports indicate that site deterioration between and within rotation in teak posses a threat to potential yield and sustainable management (Chacko, 1998). In lieu of this, rotation on teak plantation has often been shortened. In India, the rotation age of teak has been reduced from 70 years (Nair, 1998) while Thailand had reduced it to 16 years (Kaosa-ard, 1998) and Malaysia is practicing a 15 year rotation (Zakaria and Lokmal, 1998, Arias, 2003). In India, questions about the advisability of retaining the 60 year rotation is being raised (Nagesh Prabhu, 2003). However, the effect of shorter rotation on soils in teak plantations cannot now be predicted in the absence of adequate data.

A study that traces the variation in physical and chemical properties and nutrient status of teak soils with age of plantations, till the end of a rotation period is thus highly pertinent. Such a study, with an adjacent natural forest as a reference stand will not only generate information that will help us to understand the pattern of variation in soil properties, but will also aid us in formulating better management strategies. The data generated by such a study will be more useful if accompanied by information on soil changes following a short rotation plantation crop. As eucalypt, a short rotation crop is the second major plantation crop in Kerala, it was chosen for the study.

Forest plantations are now fertilized to enhance their productivity. However, fertilization in Indian context only means supply of macronutrients to plants. No thought is given to the role of micronutrients in improving the productivity. Also, differential absorption behaviors of various genotypes in the same soil are known to arise from differences in plant root characteristics. The amount and composition of root exudates also influences the availability of micronutrients to plants (Malewar, 2005). Thus, monoculture plantations can also affect soil micronutrient availability and in turn play a key role in determining the productivity. No attempt has so far been made to study the variability in micronutrients with age in plantations of teak and with rotation in plantations of eucalypt. This is a pioneer study in this field.

The organic matter is the most important constituent of soil. It not only influences the physical properties of soils but also affects the chemical properties. Organic matter in soils is highly heterogeneous in nature and its composition depends upon the nature of vegetation. Thus, replacement of natural forest by monoculture plantations may not only change the quantity of organic matter in soils but also its quality. Thus, a comparison of soil organic matter fractions in natural forest and plantations of teak and eucalypt will enhance our understanding of these ecosystems.

In this context, a detailed study that evaluates the effect of continuous growth of teak and eucalypt on soil properties, macro and micro nutrient status and organic matter fractions and comparing with soils of adjacent natural forests is highly relevant. This study thus is intended

1) **to compare the soil physical and chemical properties in teak of varying age classes and eucalypt plantations of different rotations with those of natural forest**

2) **to evaluate the micro nutrient status of soils in teak plantations of varying age class and eucalypt plantations of different rotation with those of natural forest**

3) **to characterize and assess the soil organic matter (OM) fractions in these soils**

4) **to evaluate the impact of plantation activities on soils**

1.4. Outline of the thesis

The thesis is arranged under nine chapters. The first chapter introduces the topic, reviews the literature pertaining to the study and presents the aims and objectives of the study. The second chapter briefly describes the study location, experimental design and sampling methodology. The third chapter deals with physical properties of plantation soils. The fourth and fifth chapters cover the chemical properties and macro- and micro-nutrient status in plantation soils. The organic matter fractions in plantation soils are described in sixth chapter. First part of the seventh chapter presents the results of factor analysis and the second part deals with fertility index of plantations. All these chapters are self-contained with separate introduction, materials and methods and results and discussions. A general discussion of the results is included in the eighth chapter. The ninth chapter includes conclusions and summary. This is followed by the list of references cited and appendices.

Chapter 2

Methodology

2.1. Introduction

The study was carried out in Kerala State which lies between 8° 18' and 12° 48' N latitude and 74° 52' and 77° 22' E longitude. It is a linear strip of land, extending to about 560 Km in the south-western part of India, bordered by the Arabian sea in the west and the Western Ghats in the east. It is a land highly diversified in its physical features and agro-ecological conditions. The undulating topography ranges from below the mean sea level (MSL) to 2694m above MSL. The land is panoramic with forests and plantations and picturesque with different landscapes and backwaters. The State is divided into four agro-ecological zones *viz.*, High range (750m above MSL), Highland (75-750m above MSL), Midland (7.5- 75m above MSL) and Lowland (7.5m from MSL). The main source of atmospheric precipitation is southwest and northeast monsoons and the annual average rainfall for the state is 3000mm. June to October are the wet months while November to May are relatively dry. Mean temperature is 27°C (20-42°C) and relative humidity ranges between 64% (Feb.-March) and 93% (June- July) (Anonymous, 1997).

2.2. Location of study

The study was carried out in the South Indian Moist deciduous forest, teak and eucalypt plantations in the highlands of Kerala (Plate 1-3). Although it would have been ideal had moist deciduous forest, teak and eucalypt plantations been in the same Forest Division and in close proximity with each other; but such an ecosystem was not available. However, in the Vazhachal Forest Division, there existed areas in which teak plantations of different age classes and natural forest were in close proximity and the study on impact of teak monoculture on soils was carried out in this Forest Division. Similarly, eucalypt plantations of different rotations and natural forest were in close proximity in Thrissur Forest Division and this area was selected (Fig. 1).

The Vazhachal Forest Division is located in Thrissur District, Kerala State and extends from 10°10' to 10°25' N latitude and 76°22' to 77°53' E longitudes. This Forest Division spreads over an area of 413.92 Km^2 of which 150.64 Km^2 is covered by evergreen forest. 118.69 Km^2 by grassland, 60.09 Km^2 by tea estates, 31.5 Km^2 by deciduous forest and

Fig. 1.Location of study area.

Plate 1. View of moist deciduous forest

Plate 2. View of teak plantation

Plate 3. View of eucalypt plantation

Plate 4. View of soil pit in natural forest

Plate 5. View of soil pit in teak plantation

Plate 6. View of soil pit in eucalypt plantation

29.04 Km^2 by plantations of different species. The climate is tropical, warm and humid The mean annual rainfall is 3321mm. The terrain is gently undulating.

The Thrissur Forest Division, also located in Thrissur District, Kerala State extends from 10°20' to 10°45' N latitude and 76°05' to 76°45' E longitudes. The Division has 299.46 Km^2 of forest and 8585.24 ha. of plantations of which 2025.88 ha. is covered by eucalypt plantations. The climate is tropical warm and humid. The area receives a mean annual rainfall of 2698mm. The terrain is gently undulating.

2.3. Experimental Design

There are several ways to evaluate the effect of continuous growth of teak and eucalypt on soils. Continuous monitoring of the changes in soils associated with plantation activities of teak and eucalypt over a rotation period is often impractical. Alternately this can be done indirectly

1) by assessing the rates of change for impact predictions or
2) by inference based on a chronosequence, or
3) by comparing disturbed areas to adjacent undisturbed areas.

Each one of these indirect methods makes different assumptions about the processes of soil recovery. The first one assumes that relatively short time measurements of rate of accrual and the dependence of these rates on pool sizes can accurately predict long term changes. The second one assumes that chronosequence selected for the study differs only in their age and underwent same succesional sequence and third one assumes that disturbed and adjacent undisturbed sites were similar (Johannes and Tilman, 2000).

In the present study, second and third methods were used simultaneously. Changes in soil properties in a chronosequence and comparison of the soil properties of units of chronosequence with reference stand (natural forest) were studied for better results.

2.3.1. Teak

To compare the soils in different age teak plantations with that of natural forest, age classes were developed as base line. As the plantations were established by clearfelling the natural forest, it can be assumed that initial soil conditions were similar. Hence, any variation in soil conditions in different age teak plantations can be ascertained to be the net result of plantation activities and a time sequence is reconstituted. Plantations were aggregated into four age classes *viz.*, 21-30, 31-40, 41-50 and > 51 years. As clearfelling of natural forest for establishment of plantations stopped in 1980's, first rotation plantation of 1-10 and 11-20 year age class were not available. The history of plantations was collected from Forest Department records. Only plantations that were adjacent to, or in close proximity with moist deciduous forest were selected for the study. It was also ensured that plantations selected were those directly converted to teak from natural forest.

As plantations of all age classes satisfying the above mentioned criteria were not available in one location, younger age teak plantations *viz.*, 21-40 years were selected from Karadipara and older age teak plantations *viz.*, 41-50 and >51 years were chosen at Athirapilly. Details of plantations are given in Table 1. The moist deciduous forest adjacent to the teak plantations was selected as a reference stand. For better comparison and to minimize the variation in soil properties due to local factors, soil samples from moist deciduous forest were collected from both locations.

Five sample plots, each of size 100m x 100m were laid out at random in natural forest, each one separated from the other by 200m. The number of sample plots in each plantation was in accordance with the area of the plantation. Sample plots, each of size 100m x 100m were laid out for every 20 ha. It was also ensured that a minimum of five sample plots were laid out in each age class. There were 26 sample plots in teak plantations and 10 sample plots in natural forest.

2.3.2. Eucalypt

As eucalypt in Kerala is a short rotation crop, in order to study the long-term effects of plantations on soils, rotation, rather than age was selected as the criteria. To compare the soils in eucalypt plantations belonging to different rotations with that of natural forest, second and third rotation plantations were selected. As clearfelling of natural forest for establishment of plantations stopped in 1980's, first rotation plantations were not available for study. The history of plantations was collected from Forest Department records. Only plantations which were adjacent to, or in close proximity with moist deciduous forest were chosen. It was also ensured that plantations were those directly converted to eucalypt from natural forest. The location of study was natural forest and eucalypt plantations in Thrissur Forest Division. Eucalypt plantations were those located at Chemenkandam, Marotichal and Olakkara. Among these, second rotation plantation was at Olakkara while third rotation plantations were at Chemenkandam and Marotichal. Among third rotation plantations, that at Chemenkandam was a third coppiced one while that at Marotichal was a replanted one. Thus, it was possible to study the effect of coppiced and replanted plantations on soils. All the plantations selected for the study were of the same age (five years). The second rotation plantation at Olakkara was under monoculture of eucalypts for the last 25 years, while the plantations at Chemenkandam and Marotichal were under eucalypts monoculture for the last 32 years. Details of plantations are given in Table 1.Five sample plots, each of size 100m x 100m were laid out at random in natural forest, each one separated from the other by 200m. Five sample plots, each of size 100m x 100m were also laid out at random in each plantation. There were 15 sample plots in the plantations.

2.4. Sampling Methodology

Three soil pits were dug in each sample plot. The size of the pits was 30cm x 60cm x 60cm. On gentle slopes, the pit was laid out along the direction of the slope. Soils were collected from 0-20, 20-40 and 40-60cm depths from each pit. In addition to this, soil core samples up to a depth of 60cm were also collected from the same plots in order to estimate the bulk density. A general view of the soil pits in Moist deciduous forest, and teak and eucalypt plantations is given in Plate 4-5. Soil samples from the same depths in a plot were bulked into one sample. This sample was placed on a polythene sheet and

Table 1. Details of plantations selected for study

Study area	Location	Vegetation	Age class/coppice	Name of the plantation	Elevation (MSL)
Vazhachal Forest Division	Karadipara	Moist deciduous forest	-	-	280
		Teak	21 - 30	Karadipara	200
				Rapra	210
			31 -40	Karadipara	200
				Karadipara	220
	Athirapilly	Moist deciduous forest	-	-	110
		Teak	41-50	Vadamury	80
			>50	Chully	80
Thrissur Forest Division	Marotichal	Moist deciduous Forest	-	-	100
		Eucalypt	2nd rotation coppiced	Olakkara	100
			3rd rotation replanted	Marotichal	100
			3rd rotation coppiced	Chemenkandam	100

mixed well. It was then divided into four quadrants and the soils in two opposite quadrants discarded. The remaining quadrant was again mixed well and the above process repeated until the desired amount of composite soil sample was obtained. From the oldest teak and eucalypt plantations and the adjacent natural forest, three surface samples (0-15cm) were collected from each sample plot. The three surface samples were also mixed together in a similar manner to form a composite sample. Thus, three composite soil samples from different depths and a composite surface sample were collected from each of these sample plots. A total of 188 soil samples were taken.

Soil samples were air-dried, cleaned off visible roots and ground, taking care not to break the stones, using a wooden mortar and pestle and passed through a 2mm sieve to separate the gravel from soil. The amount of gravel in each sample was recorded and the soil stored in airtight containers for further analysis.

Chapter 3

Physical Properties

3.1. Introduction

Soil physical properties profoundly influence the growth and distribution of trees through their effect on moisture regimes, aeration, temperature profiles, chemistry and the accumulation of organic matter (Dan. *et al.*, 2000). It has been reported by Evans (2000) that the vegetation types and the management activities also influence soil physical properties. Physical properties of soils in plantations and adjacent natural forests were often compared and contrasted, though no universal trends were observed. The literature in this field has been reviewed in detail in the first chapter. This chapter presents the gravel content, particle size separates, bulk density, particle density, pore space and maximum water holding capacity of the samples measured during this study.

3.2. Materials and Methods

3.2.1. Gravel

One kg of air dried soil sample, cleaned off visible roots, was ground, taking care not to break the stones, using a wooden mortar and pestle and passed through a 2mm sieve to separate the gravel from soil and weighed.

$$\text{Gravel content} = \frac{\text{Weight of the gravel}}{10}$$

3.2.2. Particle-size separates

Particle-size separates were analyzed by International Pipette method as described by Piper (1942). Twenty gram of soil was treated with 60ml of 6% hydrogen peroxide to destroy the organic matter in the soil, and with 200ml of 0.2N hydrochloric acid (200ml of 1.0N hydrochloric acid diluted to 1000ml with distilled water) to remove calcium carbonate, stirred well and kept on a water bath for 30 minutes or until effervescence ceases. The soil was washed until it was free of chlorine (test with silver nitrate solution). To this, 400ml distilled water, 8ml of 1N sodium hydroxide (40g in 1000ml distilled water) and phenolphthalein indicator was added. The whole suspension showed a pink colour. The suspension was then stirred and transferred to a 1000ml measuring jar and the made up to the mark with distilled water. The temperature of the suspension was noted and contents shaken thoroughly with repeated inversions. At the end of four minute, 20ml of the suspension was pipetted out into a pre-weighed porcelain dish (W_2) from a depth of 10cm from the surface and evaporated on a water bath. This was then dried in an oven at 105°C and weighed after cooling (W_1). This gives a measure of silt and clay. The cylinder was shaken well and at the end of six hours, 20ml of suspension was pipetted out into another weighed porcelain dish (X_2), evaporated on a water bath and dried in an oven at 105°C and weighed after cooling (X_1). This gives the amount of clay alone. The weight of silt was calculated by subtracting the weight of clay from that of silt + clay fraction. The remaining suspension was decanted into beaker by repeated washings, transferred to a preweighed dish (Y_2), dried in an oven and weighed again (Y_1). From this the weight of sand fraction was calculated.

$$\text{Per cent of clay + silt} = \frac{(W_1 - W_2 - 0.0064)*1000*100}{20 \times 20}$$

W_1 = wt. of dish +clay + silt +NaOH

W_2 = wt. of empty dish

Weight of sodium hydroxide alone = 0.0064g

$$\text{Per cent of clay} = \frac{(X_1 - X_2 - 0.0064)*1000*100}{20 \times 20}$$

X_1 = wt. of dish +clay +NaOH

X_2 = wt. of empty dish

$$\text{Per cent of sand} \quad \frac{(Y_1 - Y_2)* 100}{20}$$

Y_1 = wt. of dish + sand

Y_2 = wt. of empty dish

Per cent of silt = (% of clay + silt) – (% of clay)

3.2.3. Bulk density

Bulk density was calculated by the method described by Sankaram (1966). Bulk density of soil indicates the degree of compactness of the soil and is defined as mass per unit volume. Bulk density varies with particle size distribution, organic matter content, mechanical composition and depth of soil.

Core sample technique was used for measuringt the bulk density of soils. The length and diameter of the G.I core sampler were measured using vernier calipers. In the sample plots, the core sampler was vertivally hammered into the soil to a depth of 60cm, marked on the outside of the core sampler. The soil sticking to the outside of the core sampler was removed to enable easy withdrawl of the sampler along with the sample from the field. The bottom of the sampler was covered with a lid to prevent the soil sliding from the sampler and transported to the laboratory. The soil inside the core was pushed out using a high-pressure pump into a hemicylindrical tray with markings at 0, 20, 40 and 60 cm. This cylindrical core of soil was cut at 20, 40 and 60cm and each sample was air dried and weighed. The bulk density was calculated by using the formula

$$\text{Bulk density (g/cm}^3) = \frac{\text{Soil wt.}}{\text{Core volume}} = \frac{\text{Soil wt.}}{\Pi r^2 l}$$

Where r is the radius and l is the lenght of the core sampler.

3.2.4. Particle density

Particle density was calculated by the method described by Black (1965). Standard flasks of 25ml capacity were washed with distilled water, dried and weighed. The flasks were of varying weights (W_a). Ten gram of soil was transferred to the flask and weighed accurately (W_s). The flask was then half filled with distilled water, by adding water slowly through the sides of the cylinder, allowing it to soak the soil completely. The cylinder was then boiled gently on a water bath and tapped intermittently to remove the entrapped soil air. The flask was cooled to room temperature, filled up to the mark with cool boiled water, wiped with filter paper to remove any water sticking to the sides and weighed (W_{sw}). The flask was then emptied, washed and filled upto the mark with distilled water, wiped with filter paper and weighed (W_w). The particle density was calculated using the formula

$$\text{Particle density (g/cm}^3) = \frac{[D_w (W_s - W_a)]}{(W_s - W_a) - (W_{sw} - W_w)}$$

Where D_w = density of water

W_s = weight of flask + soil

W_a = weight of flask

W_{sw} = weight of flask+soil+ water

W_w = weight of flask + water

3.2.5. Pore space

The per cent pore space is an important soil physical property and indicates the soil volume occupied by soil air or soil water. Pore space (Sankaram, 1966) was calculated from bulk density and particle density values as described below

Pore Space = 1-(BD/PD)* 100

Where BD = Bulk Density

PD = Particle Density

3.2.6. Maximum water holding capacity

Maximum water holding capacity was calculated by the method described by Sankaram (1966). A plastic container of 8cm diameter and 9.5cm height, with holes drilled at the bottom was taken. Whatmann filter paper (No. 1) of appropriate size was placed at the bottom of the container so as to cover the holes. The container with filter paper was weighed (W_a). Soil was gently poured into the container to fill it, tapped 20 times from a height of 2cm and weighed (W_b). This was then kept overnight in a trough with sufficient water to saturate the soil. The excess water was drained and the weight determined (W_c). The maximum water holding capacity was calculated using the formula

$$\text{Max. WHC (\%)} = \frac{(\text{weight of saturated soil} - \text{weight of dry soil}) \times 100}{\text{weight of dry soil}}$$

Where, weight of saturated soil = (W_c - W_a) and weight of dry soil = (W_b - W_a)

3.2.7. Statistical analysis

From the data, both mean values and relative mean values were calculated. In order to calculate the relative mean values, the mean values of control stand i.e. natural forest was assigned a value of hundred and the relative mean values of plantations were found out and expressed as

Relative mean values = (mean values of plantations x 100)/mean values of natural forest)
It was thus possible to compare plantations which differed in their reference stand (Mishra *et al.*, 2003).

ANOVA was done for each location and for each depth level separately for comparing between vegetation. To study the soil changes over time, ANOVA was done for each age class and depth level. If the analysis of variance was found to be significant, Least Significant Difference was used for pair wise comparison. The analysis was carried out using SPSS software package (Norusis, 1988).

3.3. Results and Discussion

The mean values of soil physical properties in plantations of teak and natural forest are depicted in Table 2 and those of eucalypt and natural forest are given in Table 3. Analysis of variance (ANOVA) of soil properties due to vegetation type are presented in Appendices 1 to 12. ANOVA between soils of natural forest and different age class teak plantations and those of the natural forest and different rotation eucalypt plantations are given in Appendices 13 to 25.

3.3.1. Gravel

3.3.1.1. Teak

Gravel contents in plantations of teak ranged from 4.0 to 50.0 per cent in different depths while the variation in natural forest was from 2.0 to 21.0 per cent. In natural forest and plantations, gravel contents increased with depth except in 31-40Y age class teak plantation, where no trend was observed.

Gravel contents in the 0-20cm depth in plantations differed significantly from natural forest. Mean gravel contents in the 0-20cm depth among plantations varied from 10.9 to 12.9 per cent. The relative mean gravel contents in this depth decreased with age, higher values being observed in younger plantations. The difference between gravel contents in older plantations and natural forests was less than the difference between younger plantations and natural forest.

A clear trend could not be identified in the 20-40 and 40-60cm depths. In the 20-40cm depth, the mean gravel contents in plantations varied from 14.0 to 20.7 per cent. The younger age class plantations, viz., 21-30Y and 31-40Y, showed significantly higher gravel contents than those in the natural forest. There was no significant difference between gravel contents in older age class plantations and natural forest. In the 40-60cm depth, the mean gravel contents lay between 14.8 to 24.1 per cent. Gravel content in youngest age class plantation was significantly higher than in natural forest. In all the other plantations, no significant difference was observed.

Mean values for gravel contents in the 0-60cm depth in plantations varied from 14.4 to 19.2 per cent. The gravel contents generally decreased with age, although in >50Y age class plantation, this was not observed. The highest mean gravel content was recorded in the youngest age class plantation. Higher gravel contents were recorded in plantations of 31-40Y, 41-50Y and >50Y age class than those in the natural forest. The difference was significant in younger age class plantations, 21-30 and 31-40Y. Balagopalan (1995a, b) reported higher gravel content in teak plantations relative to natural forest. In these studies, only one age class teak plantation (21-30 year) was studied in different locations in Kerala and hence the present observation in different age class plantations cannot be compared in tote.

3.3.1.2. Eucalypt

Gravel contents in eucalypt plantations varied from 11.2 to 34.3 per cent in different depths whereas in the natural forest, the values ranged from 3.8 to 25.6 per cent. The gravel contents in soils were found to increase with depth in the natural forest. However, this trend was not clearly discernible in plantations of eucalypt.

Table 2. Mean values of soil physical properties in natural forest and teak plantations

Study area	Location	Vegetation types	Age class	Depth --cm--	Physical properties							
					Gravel	Sand	Silt	Clay	Bulk density	Particle density	Pore space	Water holding capacity
					--------%--------				----gcm^{-3}----			--%--
Vazhachal Forest Division	Site I Karadipara	Natural forest	-	0-20	4.9	66	7	27	1.02	2.39	57.3	53.4
				20-40	5.3	67	5	28	1.05	2.43	56.7	50.7
				40-60	11.5	63	12	25	1.12	2.40	53.4	49.7
				0-60	7.2	65	8	27	1.06	2.40	55.8	51.3
		Teak	21-30Y	0-20	12.9	68	12	20	1.14	2.46	53.7	46.0
				20-40	20.7	62	23	15	1.12	2.43	53.8	46.0
				40-60	24.1	65	12	23	1.15	2.49	53.8	47.5
				0-60	19.2	65	15	19	1.14	2.47	53.8	46.5
			31-40Y	0-20	12.8	69	12	19	1.19	2.52	52.8	43.1
				20-40	16.1	65	9	26	1.18	2.52	53.2	45.6
				40-60	14.8	62	10	28	1.11	2.55	56.5	43.0
				0-60	14.6	65	11	24	1.16	2.53	54.2	43.9
	Site II Athirapilly	Natural forest	-	0-20	7.3	61	18	21	0.98	2.34	58.0	53.7
				20-40	13.6	58	21	21	1.01	2.34	56.9	49.4
				40-60	14	58	21	21	1.02	2.35	56.6	49.3
				0-60	11.6	59	20	21	1.00	2.34	57.2	50.8
		Teak	40-50Y	0-20	11.7	79	11	10	1.05	2.42	57.3	47.8
				20-40	14.0	78	11	11	1.04	2.38	56.3	48.2
				40-60	17.6	78	11	11	1.05	2.41	56.3	47.9
				0-60	14.4	78	11	11	1.05	2.40	56.6	47.8
			>50Y	0-20	10.9	78	13	9	1.04	2.44	57.5	46.8
				20-40	18.6	75	13	12	1.04	2.43	57.1	47.4
				40-60	22.2	75	13	12	1.03	2.43	57.7	49.9
				0-60	17.2	76	13	11	1.04	2.43	57.4	48.0

Table 3. Mean values of soil physical properties in natural forest and eucalypt plantations

Study area	Location	Vegetation types	Rotation	Depth	Physical properties							
					Gravel	Sand	Silt	Clay	Bulk density	Particle density	Pore space	Water holding capacity
				--cm--	----------%----------				------gcm^{-3}------		--%--	
Thrissur Forest Division	Marotichal	Natural forest	-	0-20	5.9	75	9	16	0.96	2.34	58.4	55.8
				20-40	15.8	75	8	17	1.04	2.18	52.3	52.4
				40-60	23.2	74	10	16	1.18	2.47	52.3	51.0
				0-60	15	75	9	16	1.06	2.33	54.3	53.1
		Eucalypt	Rotation 2 coppiced	0-20	14.1	87	7	6	1.14	2.42	52.9	48.7
				20-40	23.3	84	8	8	1.23	2.56	51.9	46.8
				40-60	23.2	84	8	8	1.25	2.55	52.9	47.6
				0-60	20.2	85	8	7	1. 21	2.51	51.9	47.7
			Rotation 3 coppiced	0-20	19.1	80	11	9	1.12	2.37	52.8	51.6
				20-40	19.7	78	11	11	1.18	2.38	50.5	48.8
				40-60	22.3	77	10	13	1.23	2.44	50.5	48.1
				0-60	20.4	78	11	11	1.18	2.40	51.3	49.5
			Rotation 3 replanted	0-20	16.5	84	7	9	1.09	2.30	52.7	52.7
				20-40	17.8	81	9	10	1.10	2.31	52.4	47.4
				40-60	20.0	79	10	11	1.23	2.32	50.4	49.8
				0-60	18.1	81	9	10	1.14	2.31	51.8	49.9

In the 0-20cm depth, plantations recorded significantly higher amounts of gravel than those in the natural forest. The mean gravel contents in plantations ranged from 14.1 to 19.1 per cent. There was significant increase in the gravel contents with rotation. The mean gravel contents in second, third and third rotation replanted plantations were greater than those in the natural forest by 140, 223 and 180 per cent, respectively. There was no significant difference in gravel contents between third rotation coppiced and replanted plantations. Balagopalan (1992, 1995b) also recorded lowest values in moist deciduous forest when compared with eucalypt plantations under different rotations in a different locations.

The mean gravel contents in plantations were higher than those in the natural forest in the 20-40cm depth. The mean gravel contents in plantations ranged from 17.8 to 23.3 per cent. The relative mean values in second and third rotation and third rotation replanted plantations were 148, 125 and 113 per cent, respectively.

In the 40-60cm depth, mean gravel contents in plantations varied from 20.0 to 23.2 per cent. The plantations had lower gravel contents than those in the natural forest. The relative mean values for gravel in second and third rotations and third rotation replanted were 100, 91 and 86 per cent, respectively. In general, no significant difference in gravel contents was observed between natural forest and plantations at 20-40 and 40-60cm depth, though a significant difference was observed between natural forest and second rotation eucalypt in 20-40cm.

A significant increase in gravel content was observed generally in eucalypt plantations compared to natural forest in the 0-60cm depth. All the plantations recorded higher gravel contents than natural forest and the difference was significant between natural forest and second rotation and third rotation coppiced eucalypt plantations. In the second and third rotation plantations, the gravel contents were very close to each other. The relative mean values for gravel in second rotation, third rotation and third rotation replanted were 135, 136 and 121 per cent, respectively. Significantly higher gravel contents in plantations were reported by Balagopalan (1987) in successive rotation

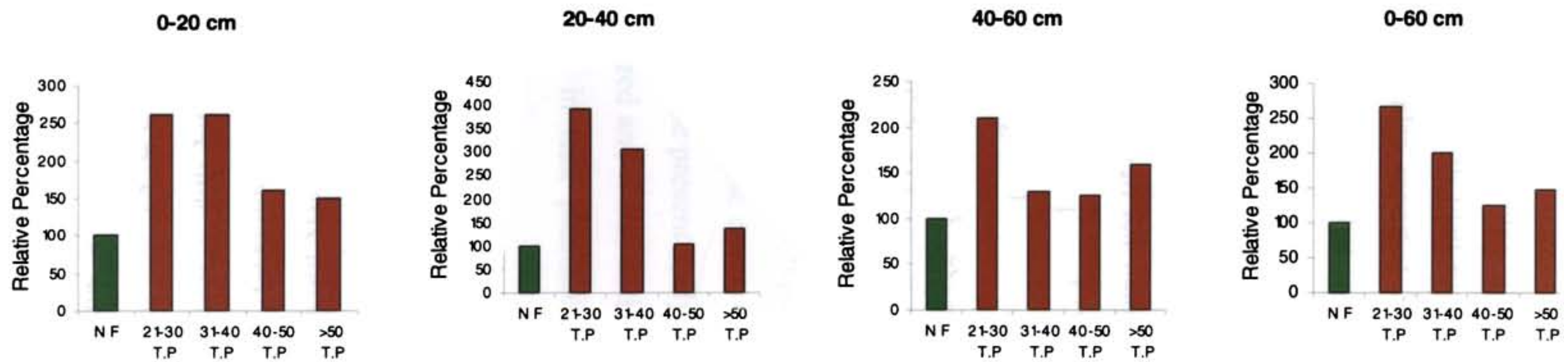

Fig. 2. Relative mean values of gravel content at different depths in natural forest and teak plantations

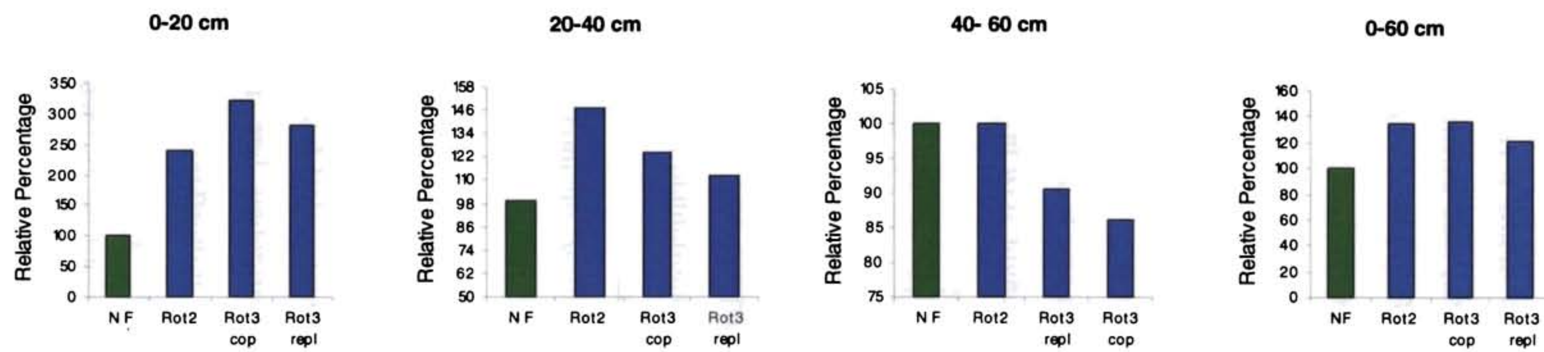

Fig.3. Relative mean values of gravel content at different depths in natural forest and eucalypt plantations

eucalypt plantations while the observation of Balagopalan and Jose (1993) was limited to a first coppiced plantation. However, there was no study in third rotation replanted area.

3.3.1.3. Comparative evaluation

When the effect of monoculture plantations on soils as a whole was studied, it was observed that soils of plantations had higher gravel contents than natural forest. Similar findings were also reported earlier by Balagopalan and Jose (1993) and Balagopalan (1995b). It was noted that in the top 20cm soil depth, gravel contents increased with rotations though the difference was not significant. When soils under plantations of teak and eucalypt over similar periods were compared, it was observed that in the 20-30 year period (2nd rotation), soils under eucalypts had lower relative mean gravel values than those under teak (240 per cent and 262 per cent, respectively). But, when soils under plantations of 30-40Y period (3rd rotation) were considered, it was noticed that relative mean values for gravel contents in plantations of eucalypt were higher than those in teak (260 and 323 & 280 per cent, respectively). As large scale eucalypt plantations were initially established during the period 1970-80, it was not possible to study the soils which were under eucalypts for more than 40Y. Higher gravel content in eucalypt soils relative to teak was earlier reported by Balagopalan (1995b) and Geetha and Balagopalan (2005b). In both these cases, only one plantation of teak was compared with eucalypt plantations. In the present study, soils in teak and eucalypt plantations for the same period were compared and it was noticed that though initially, the relative mean gravel contents were higher in teak plantations, later more gravel contents were found in eucalypt plantations.

The very process of plantation establishment, which involves clearfelling of natural forest, exposes the soil to disruptive forces of nature like wind, rain and sunlight. The balance in natural climax forest is disturbed (Geetha and Balagopalan, 2005a). The loss of soil cover (accumulated litter), canopy cover and undergrowth, coupled with disturbances at the time of burning the slash and the site preparation for establishment of plantation causes accelerated soil erosion. During erosion, the top soil is most susceptible to loss. In some cases, the subsurface layer is exposed to the surface. In an alternative scenario, gravel would be left behind and fine particles lost from the surface. Both these processes lead to higher gravel contents in plantation soils. Due to longer rotation period of teak plantations, as the plantations grow old, accumulation of the litter on the ground, partial canopy closure and the growth of under-story in plantations lead to decreased rate of erosion which translates into a general trend of decline in relative gravel per cent with age. This trend is more clearly visible in the 0-20cm depth, which is the layer most affected by plantation activities.

The decline in gravel per cent with age observed in teak were not observed in eucalypt plantations. This is because eucalypt being a short rotation crop (7 to 10 years), repeated exposure of soils to adverse environmental factors are more frequent. Similar observation was made by Balagopalan (1992). Teak being a long rotation crop, soil has an opportunity to recuperate and as a result, gravel content in older teak plantations and natural forest were not significantly different from each other in the 0-60cm depth.

3.3.2. Particle size separates

3.3.2.1. Teak

Soils in younger age teak plantations and natural forest were sandy clay loam while in older teak plantations, the soils were sandy loam. As the plantations were established after clearfelling natural forest, it can be assumed that soils in the plantations were initially similar to those in the natural forest. It was also noticed that the soil texture did not vary with depth in the natural forest. After clearfelling and during the initial years of establishment of plantations, the soils were exposed to the environmental factors. In the younger plantations, periodical thinning, both mechanical and silvicultural, expose the soil. These might have led to the loss of surface layer, exposing the subsurface layer. As both surface and subsurface layers were of the same textural class, no apparent difference in the texture was immediately noticed, though an increase in gravel was observed. In older teak plantations, even though erosion continues, it is not as intense as in the beginning due to partial canopy closure, presence of litter, undergrowth etc. As a result, rather than the complete loss of topsoil, continuous loss of finer particles was noted in older plantations. This incessant loss of finer particles results in the change of textural class from sandy clay loam to loamy sand in older plantations. This finding is at variance from the conclusions of Okoro *et al.* (1999, 2000) who observed that the texture of the soils was not affected by the respective plantation species but agrees with the findings of Balagopalan (1995b).

3.3.2.2. Eucalypts

Soils of eucalypt plantations were loamy sand while in natural forest, the soils were sandy loam. Initially, the plantations were established after clearfelling natural forest, and during the early years, the soils were exposed to the environmental factors resulting in the loss of top soil and fine fractions from the subsurface layers. As eucalypt is a short rotation crop, the soils were exposed to the vagaries of nature more frequently, *viz*., every 7-10 years. Moreover, lack of undergrowth and incomplete canopy closure due to the conical nature enhances soil erosion. Soils were also disturbed severely during harvesting. The resultant incessant loss of finer particles leads to a change of textural class from sandy loam to loamy sand. A change in textural class *viz*., from loam to loamy sand was reported by Balagopalan (1992) and a significant coarsening of texture was observed in *E. camaldulensis* plantations than under natural vegetation in Nigeria (Jaiyeoba, 1995).

3.3.2.3. Comparative evaluation

The study has conclusively demonstrated that soils under plantations, whether teak or eucalypts, have higher amount of coarse fractions and lower amount of fine fractions than under natural forest, consequent to the plantation activities. Higher coarse fractions in plantation soils were also reported by Balagopalan and Jose (1997) and Rathod and Devar (2003a).

3.3.3. Bulk density

3.3.3.1. Teak

Bulk density values in teak plantations were generally higher than in natural forest. The values ranged from 0.97 to 1.28gcm^{-3} in the plantations and in the natural forest. the values varied between 0.97 and 1.25gcm^{-3}.

Bulk density values in all the plantations were significantly higher than those of natural forest in the 0-20cm depth. At this depth, an increase in mean bulk density values with age in younger plantations was followed by a decrease in older plantations and then stabilization at the lowered values. The mean values for bulk density in older plantations *viz.*, 41-50Y and >50Y were nearly similar. The relative mean bulk density values for 21-30Y, 31-40Y, 41-50Y and >50Y age classes were 112, 118, 107 and 106 per cent, respectively. The mean bulk density values were in the range of 1.04 to 1.19gcm^{-3}. Enhanced bulk density values in a teak plantation in Nigeria was reported by Aborisade and Aweto (1990). A similar finding was reported by Balagopalan (1995b) from Kerala. However, in the present study an interesting observation was the decrease in relative bulk density values in older plantations.

In the 20-40cm depth, the mean bulk density values ranged from 1.04 to1.18gcm^{-3}. The pattern of variation in this depth was same as that of the previous depth. The relative mean values of bulk density in the 21-30, 31-40, 41-50 and >50Y age classes were 107, 112, 103 and 103 per cent, respectively.

In the 40-60cm depth, no definite trend in bulk density values was discernable. The relative mean bulk density values for 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 103, 99, 103 and 101 per cent, respectively and the mean bulk density values varied between 1.03 to1.15gcm^{-3}. Amponsah and Meyer (2000) also reported significant increase in bulk density values in soils of natural forests converted to teak.

In the 0-60cm depth, there was not much variation in the bulk density values in the natural forest and plantations. The highest relative mean value for bulk density was recorded in 31-40Y age class plantation and the lowest value was recorded in the oldest age class *viz.*, >50Y. The difference was significant in 31-40Y age class plantations. The relative mean values of bulk density in the 0-60cm depth for 21-30, 31-40, 41-50 and >50Y age classes were 107, 109, 105 and 104 per cent, respectively and the mean bulk density values varied from 1.00-1.16gcm^{-3}. Increased compaction in teak plantations was also reported by Jose and Koshi (1972), Amponsah and Meyer (2000) and Rathod and

On studying the soils in the 0-60cm depth, it was observed that plantations recorded higher bulk density values than natural forest and the difference was significant in all plantations. Bulk density values in the third rotation plantations were very close and did not differ significantly from each other. The mean bulk density values varied from 1.14 to 1.21gcm^{-3}. The relative mean values for second rotation, third rotation coppiced and third rotation replanted plantations were 114, 111 and 107 per cent, respectively. Balagopalan and Jose (1993) and Jaiyeoba, (1995) also found increased compaction in plantations of eucalypt compared to natural forest. But the extent of increase varied.

3.3.3.3. Comparative evaluation

Soils of both teak and eucalypt plantations were more compacted than natural forest. Similar observations were made by Jose and Koshi (1972), Ram and Patel (1992), Bargali *et al.* (1993), Jaiyeoba (1995), Balagopalan and Jose (1997), Amponsah and Meyer (2000) and Rathod and Devar (2003a). In the natural forest, the bulk density values increased with depth. A similar trend was not generally observed in plantation soils.

Mechanical compaction of the soils during clearfelling of natural forest and also during the initial stages of plantation establishment may be responsible for higher compaction in plantation soils. It was also noticed that difference between the bulk density values of natural forest and plantations was most pronounced in the surface. This could be due to the loss of loose surface soil due to plantation activities.

When soils, in plantations of teak and eucalypts, over similar periods were compared, it was observed that in the 21-30 year period, soils under eucalypt were more compacted than teak. During the 31-40Y period, both the plantations had similar increase in bulk density values.

In the 0-20cm depth, both plantations had higher bulk density values than natural forest. During the 21-30Y period, soils in eucalypt plantations recorded a 17 per cent rise in mean bulk density against the 12 per cent rise observed in teak. Higher compaction (30 per cent) in soils of eucalypt compared to teak was reported by Balagopalan (1995b).

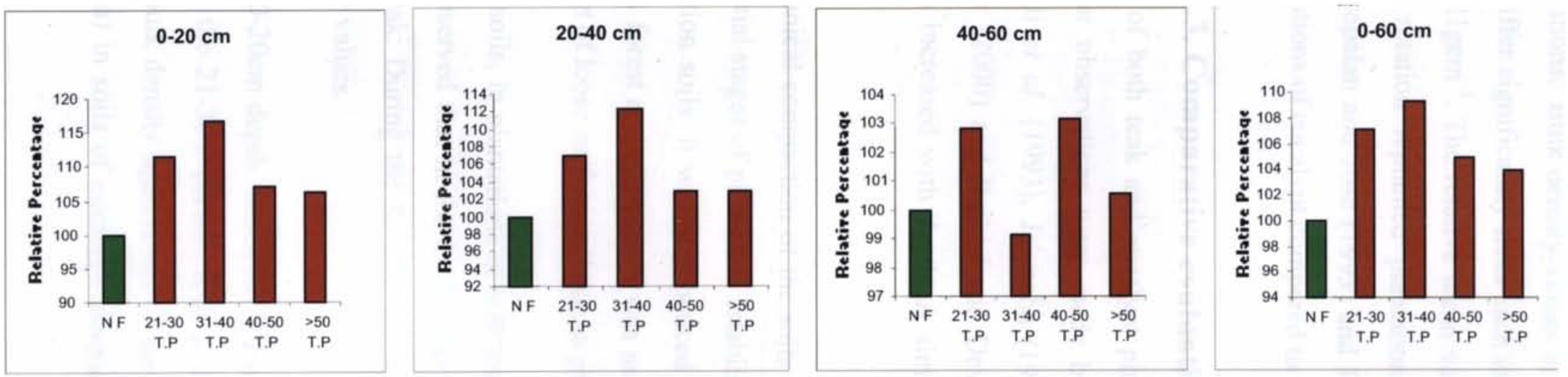

Fig. 4. Relative mean values of bulk density at different depths in natural forest and teak plantations

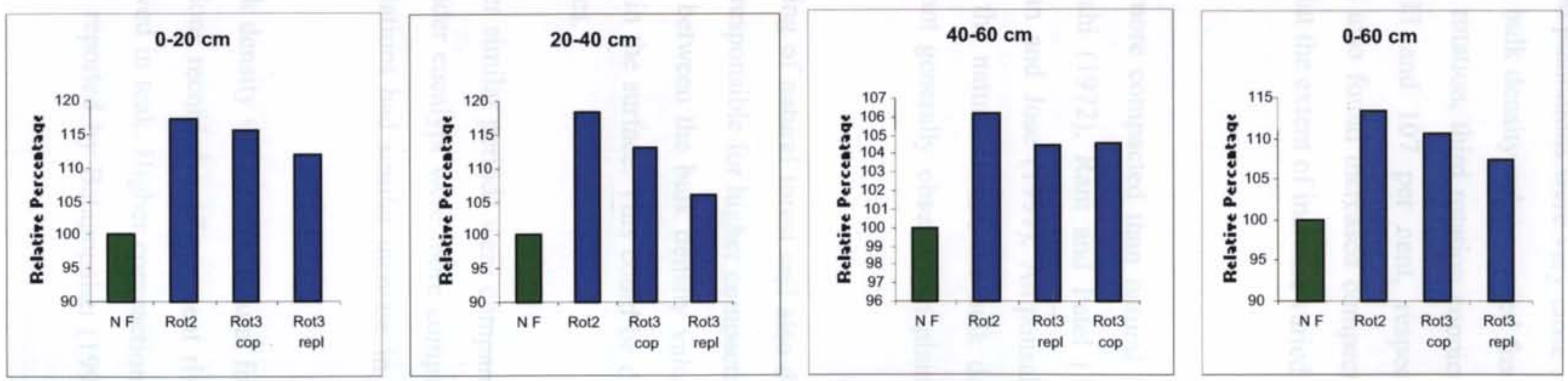

Fig. 5. Relative mean values of bulk density at different depths in natural forest and eucalypt plantations

However, during the 31-40Y period, lower mean bulk density values were recorded in plantations of eucalypt than in teak. In the 20-40cm depth, the same pattern of variation was observed. When the soils of 0-60cm depth as a whole was considered, greater compaction was observed in plantations of eucalypts than teak. In the case of eucalypt plantations, shorter rotation period results in more frequent exposure of soil to the environmental forces without sufficient time for the soil to recuperate. This may be responsible for the greater compaction in eucalypt than teak.

Mean bulk density values in all the teak plantations were significantly higher than those in the natural forest in the 0-20cm depth. At this depth, an increase in bulk density values with age in younger plantations was followed by a decrease in older plantations and then stabilization at the lowered values. Mechanical compaction and enhanced erosion during clear felling followed by periodic silvicultural thinning in the initial years of plantation establishment might be responsible for the higher compaction in younger teak plantation soils. As the frequency and extend of disturbance to soil decreases with the age of the plantation, compaction decreased in older teak plantations.

3.3.4. Particle density

3.3.4.1. Teak

Particle density values in plantations varied from 2.32-2.68gcm^{-3} while in natural forest the values ranged from 2.22 to 2.55gcm^{-3}. No definite relationship was observed between particle density values and depth in the soils of natural forest and plantations. In the 0-60cm depth, there was not much variation in the particle density with age. Mean particle density values varied from 2.40-2.53gcm^{-3}. The highest relative mean particle density value was reported in the 31-40Y age class plantation and the difference from natural forest, though small, was significant.

When the soils in the 0-20cm depth were studied, it was observed that the particle density values in plantations and natural forest were very close. Mean particle density values varied from 2.42-2.52gcm^{-3}. The relative mean values of 21-30, 31-40, 41-50 and >50Y age class plantations were 103,106,105 and 106 per cent, respectively.

In the 20-40 and 40-60cm depths, no definite trend was seen. The mean particle density values ranged from 2.38-2.52gcm^{-3} in 20-40cm depth and in 40-60cm depth, the values varied from 2.41-2.55gcm^{-3}. The relative mean particle density values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations, in the 20-40cm depth were 100, 104, 102 and 104 per cent, respectively. In the 40-60cm depth, the corresponding values were 104, 107, 105 and 103 per cent, respectively. This showed that there was not much variation in particle density values in plantations when compared with natural forest. A study by Balagopalan and Jose (1993) on soils in teak plantations and natural forest also found that particle density values in plantations were very close to those in the natural forest.

3.3.4.2. Eucalypts

Particle density values in plantations varied from 2.02 to 2.63gcm^{-3} while in the natural forest, the values were in the range of 2.13 to 2.60gcm^{-3}. Particle density values were not found to vary with depth in either soils of natural forest or plantations. The mean particle density values in eucalypt plantations did not differ significantly from natural forest in the 0-20cm depth. The values in plantation soils varied between 2.30 to 2.42gcm^{-3}. The relative mean values for second rotation, third rotation and third rotation replanted plantations were 104, 101 and 98 per cent, respectively.

In 20-40cm depth, the mean values ranged from 2.31 to 2.56gcm^{-3}. The relative particle density values in the second rotation plantation was 17 per cent greater than that in natural forest while that in the third rotation and third rotation replanted plantations were greater than natural forest by nine and six per cent, respectively. However the difference from natural forest values was non significant.

In the 40-60cm depth, the mean particle density values ranged from 2.32 to 2.55gcm^{-3}. But, no definite relationship was observed between particle density values and rotation. The relative particle density values for second rotation, third rotation and third rotation replanted plantations were 103, 96 and 94 per cent, respectively.

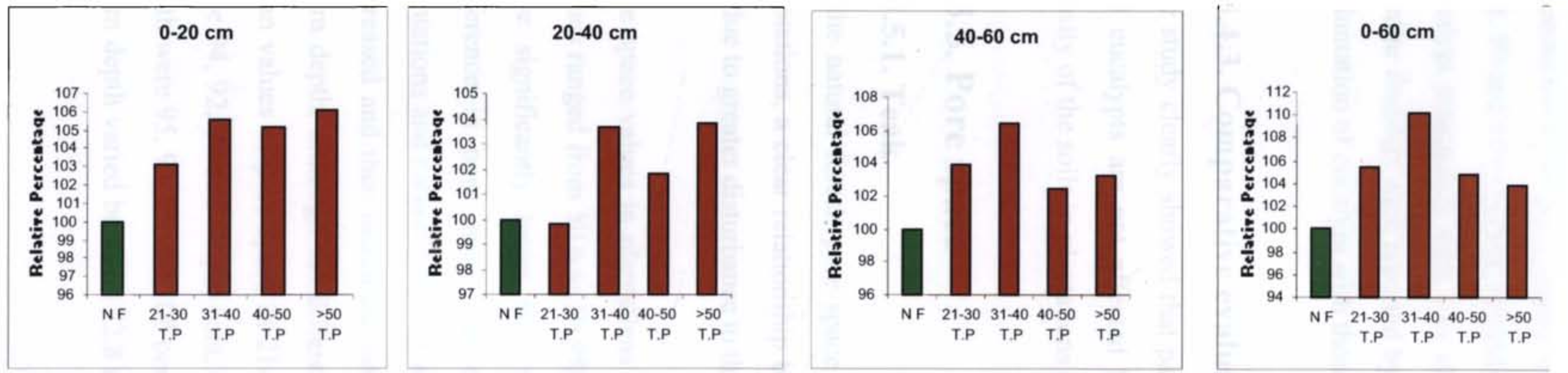

Fig.6. Relative mean values of particle density at different depths in natural forest and teak plantations

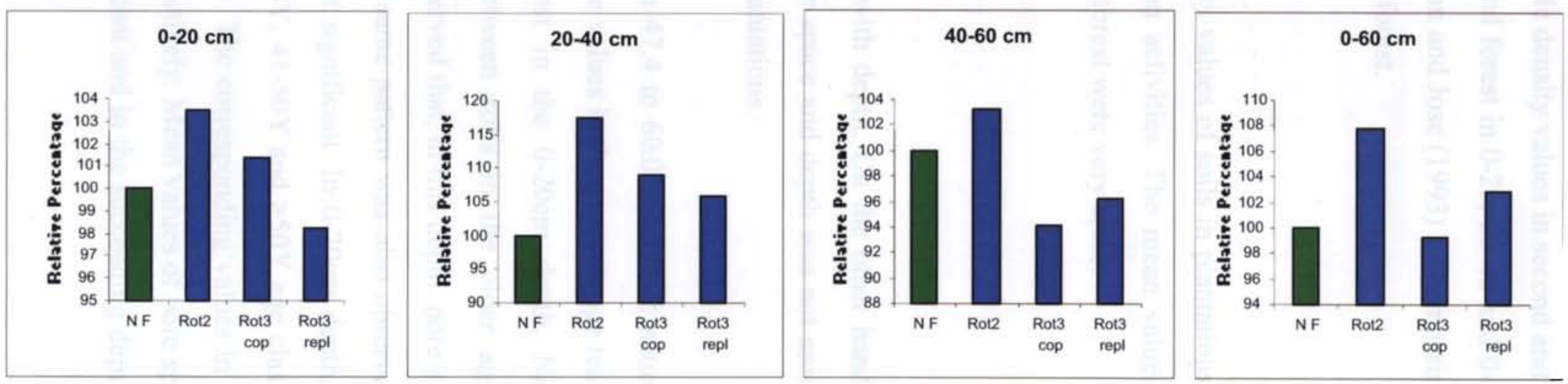

Fig.7. Relative mean values of particle density at different depths in natural forest and eucalypt plantations

In the 0-60cm depth, the mean values of particle density in plantations of eucalypts varied from 2.31 to 2.51gcm^{-3}. The relative mean values of particle density for eucalypt plantations of second rotation, third rotation coppiced and third rotation replanted were 108, 99 and 103 per cent, respectively. Particle density values in second and third rotation eucalypt plantations were very close to natural forest in 0-20, 20-40 and 0-60cm depths. Similar findings were reported by Balagopalan and Jose (1993) by comparing the soils in a plantation of eucalypt with those of natural forest.

3.3.4.3. Comparative evaluation

The study clearly showed that particle density values of soils in plantations of both teak and eucalypts are not affected by plantation activities. The mean values for particle density of the soils in plantations and natural forest were very close.

3.3.5. Pore space

3.3.5.1. Teak

In the natural forest, pore space decreased with depth. On the other hand, in the teak plantations, a clear relationship between pore space and depth was not seen. This could be due to greater disturbance to the soils in plantations.

Pore space values in plantations varied from 47.4 to 60.0% while in natural forest the values ranged from 50.6 to 59.9%. Pore space values in the younger age teak plantations were significantly lower than natural forest in the 0-20cm depth. No significant difference in pore space was observed between soils in the older age class teak plantations and natural forest. It was also observed that, in this depth, pore space initially decreased and then increased with age. The same pattern was also observed in the 20-40cm depth, although the difference was not significant. In 0-20cm depth, the relative mean values of pore space in 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 94, 92, 99 and 99 per cent, respectively. The corresponding values in the 20-40cm depth were 95, 94, 99 and 100 per cent, respectively. Mean values of pore space in the 0-20cm depth varied between 52.8 to 57.5 per cent and in the succeeding depth, the values ranged from 53.2 to 57.1 per cent. There was no definite pattern or significant difference between teak plantations and natural forest in the 40-60cm depth. Mean pore space values in the 40-60cm depth varied from 53.8 to 57.7 per cent and the relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 101,106, 100 and 102 per cent, respectively.

When soils in the 0-60cm depth in different age class plantations were studied, it was observed that, pore space increased with the age of the plantations and in the oldest age class, the values were close to that of natural forest, and the difference was non-significant. The relative mean values of pore space in the 21-30Y, 31-40Y, 41-50Y and >50Y age classes were 96, 97, 99 and 100 per cent, respectively. Mean pore space values in the 0-60cm depth varied from 53.8 to 57.4 per cent. Lower pore space values in plantation soils were reported by Geetha and Balagopalan (2006). However, these studies were restricted to a single plantation of teak and adjacent natural forest and did not report the decrease in compaction seen in older plantations.

3.3.5.2. Eucalypts

Pore space values in plantations varied from 48.3to 55.1% while in natural forest the values ranged from 49.9 to 61.3%. A significant decline in pore space values in plantation soils relative to natural forest was seen in 0-20cm depth. The relative mean values for second rotation, third rotation coppiced and third rotation replanted plantations were 91, 90 and 90 per cent, respectively. No significant difference was observed between pore space values of natural forest and plantations in the 20-40 and 40-60cm depths. The relative mean values for second rotation, third rotation coppiced and third rotation replanted plantations were 99, 96 and 100 per cent, respectively in the 20-40cm depth. The relative mean value for pore space in the plantations in 40-60cm depth was 97 per cent.

Soils in all the plantations of eucalypts had significantly lower pore space values than natural forest in 0-60cm depth. The relative mean values for second rotation, third rotation and third rotation replanted plantations were 96, 94 and 95 per cent, respectively. Lower pore space values in plantation soils were reported by Balagopalan and Jose

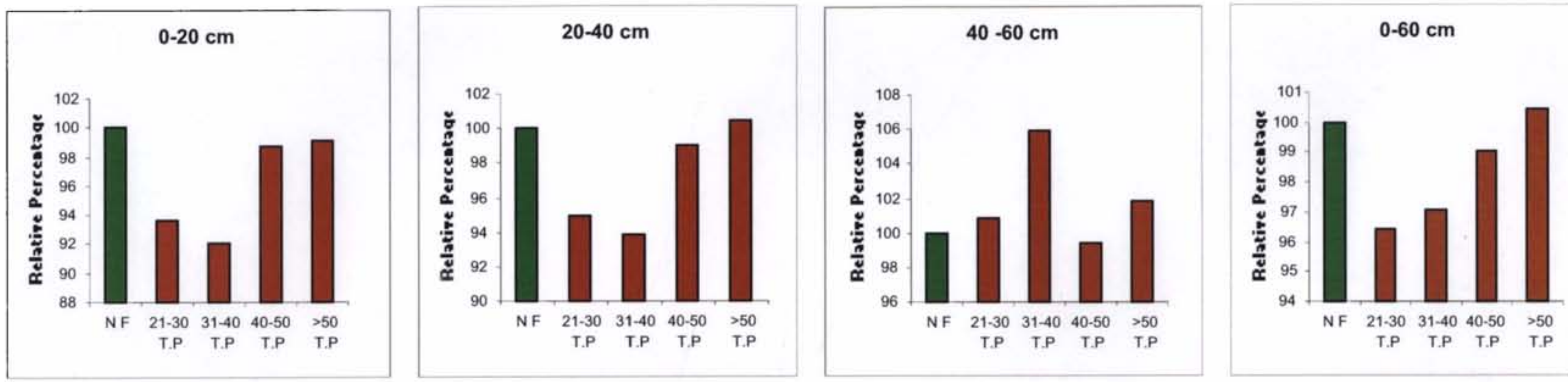

Fig.8. Relative mean values of pore space at different depths in natural forest and teak plantations.

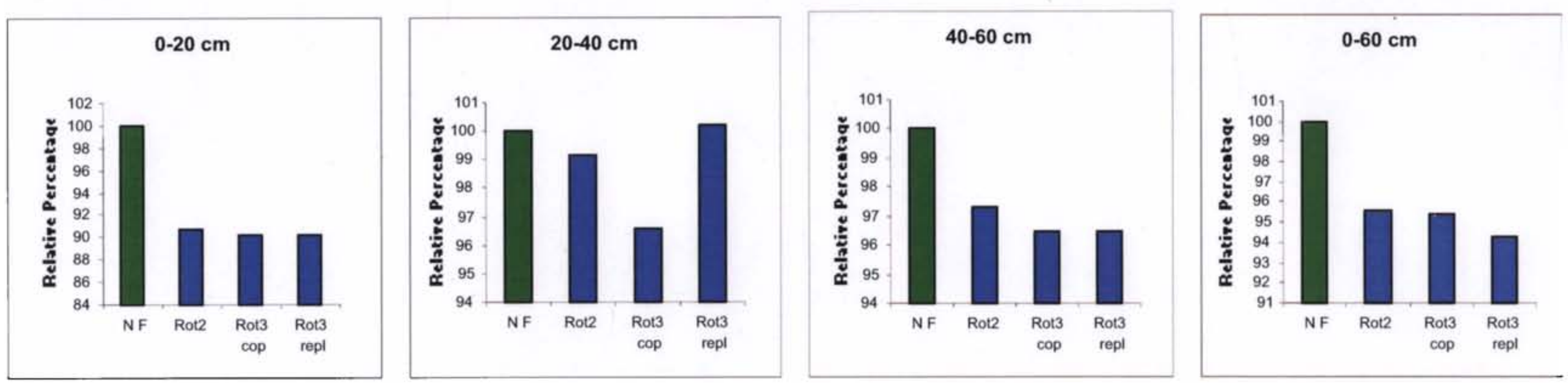

Fig.9. Relative mean values of pore space at different depths in natural forest and eucalypt plantations

(1993) and Bargali *et al.* (1993). The study by Balagopalan and Jose (1993) was restricted to a single plantation of eucalypt and adjacent natural forest while that of Bargali *et al.* (1993) was limited to a single rotation.

3.3.5.3. Comparative evaluation

In natural forest. pore space values were found to decrease with depth. However, such a pattern of variation could not be observed in plantations of eucalypts or teak. Soils of natural forest are undisturbed; on the other hand in plantations, the disturbance to soil is much greater, hence the absence of a definite pattern.

A significant decline in pore space values was observed in the 0-20cm depth in both plantations. In the 0-60cm depth, pore space in soils of natural forest and plantations of teak were not significantly different from each other. On the other hand, in eucalypt plantations, a significant decline was observed. In the 21-30Y period, a 10 per cent lowering of mean pore space values was observed in eucalypt plantations. During the same period, soils in teak plantations recorded six per cent lower values. During the 31-40Y period, mean pore space values in plantations of eucalypts was lower than natural forest by 10 per cent while in teak, the difference was 8 per cent. Lower pore space in plantations of eucalypt compared to teak was previously reported by Balagopalan and Jose (1993) and Bargali *et al.* (1993). The study of Balagopalan and Jose (1993) was in a single plantation each of teak, eucalypt and adjacent natural forest. Pore space values were significantly and negatively correlated with bulk density.

3.3.6. Water holding capacity

3.3.6.1. Teak

Water holding capacity decreased with depth in natural forest. However, such a specific pattern of variation was not observed in plantations of teak. This could be due to the soil disturbance in plantations. In natural forest, water holding capacity varied from 46.3 to 55.6 per cent while in plantations, the values varied between 36.2 to 55.7 per cent.

Mean values of water holding capacity in plantations of teak varied from 43.1 to 47.8 per cent. A significant decline was noted in plantation soils compared to natural forest in the 0-20cm depth. In plantations, the values initially decreased and then increased with age. The lowest value for relative water holding capacity was recorded in 31-40Y age class plantations. The relative mean values in 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 89, 84, 89 and 87 per cent, respectively.

Relative mean values of water holding capacity of soils in the 20-40cm depth was lower in younger age class plantations than in older plantations. The values in the younger teak plantations were significantly lower than natural forest. Mean water holding capacity values varied between 45.6 to 48.2 per cent and the relative mean values for 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 91, 90, 98 and 96 per cent, respectively.

In the 40-60cm depth, mean values for water holding capacity varied between 43.0 to 49.9 per cent and the relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 96, 87, 97 and 101 per cent, respectively. Water holding capacity values were found to initially decrease and then increase with age. Soils in older teak plantations and natural forest had similar water holding capacity values.

When water holding capacity of soils in the 0-60cm depth was considered, it was observed that mean values varied between 43.9 to 48.0 per cent. A significant lowering of water holding capacity relative to natural forest was observed in the 21-30Y and 31-40Y age class plantations. In older teak plantations, the difference was non significant. The values in plantations initially decreased and later increased with age and stabilized in the older plantations. The highest relative mean value was recorded in the oldest age class (95 per cent). Plantations of 21-30Y, 31-40Y and 41-50Y age classes showed relative mean values of 92, 86 and 94 per cent, respectively. Dagar *et al.* (1995) and Geetha and Balagopalan (2005b) also reported lower water holding capacity in soils of teak plantations relative to natural forest. These studies were limited to a single plantation of teak and as such provide no information about variation of water holding capacity with age.

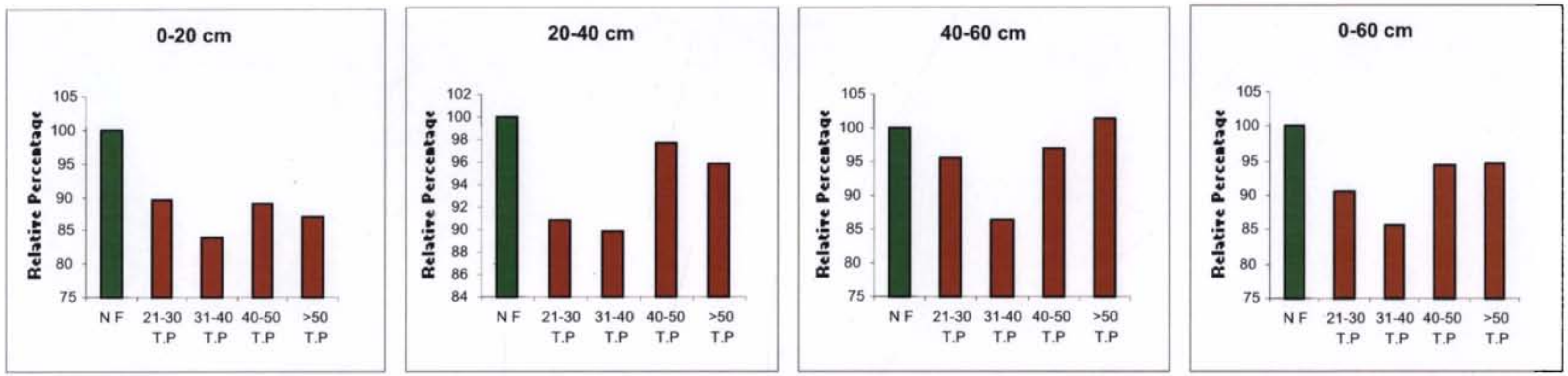

Fig.10. Relative mean values of water holding capacity at different depths in natural forest and teak plantations

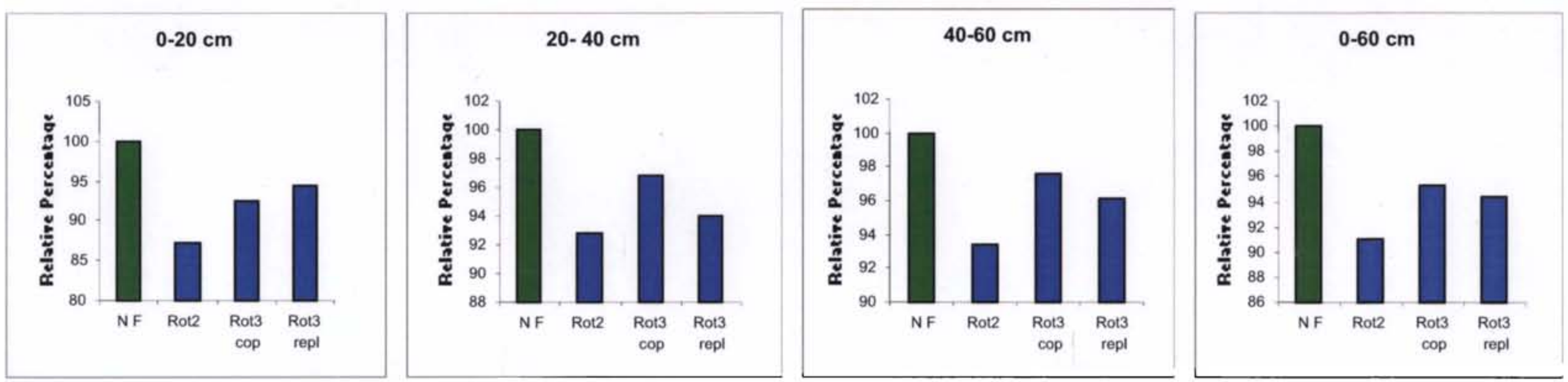

Fig.11. Relative mean values of water holding capacity at different depths in natural forest and eucalypt plantations

3.3.6.2. Eucalypts

A decrease in water holding capacity values with depth was observed in soils of natural forest while in plantations of eucalypt, this trend was not observed. Water holding capacity values in the natural forest soils were significantly higher than those in the eucalypt plantations in all the three depths. Water holding capacity values in natural forest varied from 46 -58 per cent while in eucalypt plantations, the variations were from 40 to 54 per cent.

In the 0-60cm depth, the relative mean water holding capacity values in the second rotation, third rotation coppiced and third rotation replanted plantations were 91, 95 and 95 per cent, respectively. It was observed that water holding capacity values in plantation soils were significantly lower than those in the natural forest in the 0-20, 20-40cm and 0-60cm depths. The same trend was also observed in the 40-60cm depth, though the difference between second rotation and third rotation plantation was not significant.

The relative mean water holding capacity values in the second rotation, third rotation and third rotation replanted plantations in the 0-20cm depth were 87, 93 and 95 per cent, respectively. The relative mean water holding capacity values in the 20-40 and 40-60cm depths in the second rotation, third rotation and third rotation replanted plantations were 93, 97 and 94 per cent and 93, 98 and 96 per cent, respectively. A significant decrease in water holding capacity of plantation soils compared to that of natural forest was also reported by Balagopalan and Jose (1993, 1995) and Bargali *et al.* (1993).

3.3.6.3. Comparative evaluation

A decrease in water holding capacity values with depth was observed in natural forest whereas in the plantations of teak and eucalypt, such a pattern was not seen. Both the plantations had lower water holding capacity values than natural forest. Balagopalan and Jose (1993, 1997) and Geetha and Balagopalan (2005b) recorded similar findings in a single teak and eucalypt plantations.

It was reported by Balagopalan (1987) that soils in teak plantations had slightly lower water holding capacity than in eucalypt plantations of different rotation. In the present study the comparison was made between teak plantations of different age classes and eucalypt plantations of different rotations and it was seen that there is a decreasing trend in younger plantations and an increasing trend in older plantations. In the eucalypt plantations, no definite pattern was seen.

Chapter 4

Chemical Properties

4.1. Introduction

In forest ecosystems, trees affect soil properties through several pathways. They are paths through which nutrients cycle and sites for the accumulation of nutrients within a landscape (Rhoades, 1996). Monoculture plantations differed from natural forest in quantity of litter, nutrient content and rate of decomposition (Singh *et al.*, 1993; Pande and Sharma, 1993a; Pande and Sharma, 1993b; Sankaran, 1993; Maharudrappa *et al.*, 2000 and Panda and Swain, 2002). Thus surface soils with similar soil parent materials, ground cover and topography but with different vegetation types were found to differ in their soil properties (Singh *et al.*, 1988). The conversion of natural forest to monoculture plantations affected the chemical properties and nutritional status of soils (Mongia and Bandyopadhyay, 1992a; Balagopalan 1995a; Dagar *et al.*, 1995; Michelsen *et al.*, 1996; Joshi *et al.*, 1997; Lian and Zhang, 1998; Aweto 2001; Pande, 2004; Guo-Jian Fen *et al.*, 2004).

Results of soil studies under plantation forests may differ from one geographical region to another even under the same tree species. Many factors explain these differences. The abundance of soil nutrients is controlled by several factors including the intrinsic soil nutrient status. If the soils of the study area are comparatively rich in nutrients, their status may remain unchanged for a short period by plantation activity. On the other hand, in nutritionally poor soils, the nutrient status may change more easily. Similarly, the demand for soil nutrients by tree crops is at peak during the establishment phase. After canopy closure, additional growth consists of accumulation of wood which is a tissue with lower nutrient content, and tree nutrient demand is met through internal nutrient recycling. Also, break down of litter by microbial activity makes available the nutrients, which supplement those lost or absorbed by the trees. Thus mature tree demands less nutrients from the soil and may allow enough time for replenishment to take place (Maro, 1993). Thus, rotation age can also influence soil properties.

The major limitations of tropical soils in short rotation tree crops are low nutrient reserves, poor nutrient retention ability and susceptibility to drought (Tiarks *et al.*, 1998). Shorter rotation is thought to result in long-term decline in soil carbon content as there is more frequent cultivation and disruption to the flow of carbon to the soil through litter (Polglase *et al.*, 2000). Intensive harvesting would also increase nutrient loss from the site by removal in the wood and other losses (Folster and Khanna, 1997; Goncales *et al.*, 1997).

Chemical properties and macronutrient status of soils in plantations and adjacent natural forests were often compared and contrasted, but no universal trends were observed. The literature in this field has been reviewed in detail in the first chapter. In the present study, soil pH, exchangeable bases, organic carbon, total nitrogen, exchangeable sodium, potassium, calcium, magnesium and phosphorus in plantations and adjacent natural forests were estimated and compared.

4.2. Materials and Methods

4.2.1. Soil pH

The soil pH was determined in a 1: 2.5 (water) suspension by using CYBERSCAN 510 pH meter (Jackson, 1958). The pH meter was calibrated for pH 4.0, 7.0 and 9.2 using buffer solutions, prepared from readily available buffer tablets. Ten gram of air-dried soil was weighed accurately in a beaker and 25 ml of distilled water was added. The contents were stirred with a glass rod and allowed to stand for 30 minutes. The pH of the supernatant solution was measured with utmost care with the glass electrode just touching the soil layer.

4.2.2. Exchangeable bases

Exchangeable bases were found out by shaking 10g soil with 0.1N hydrochloric acid (8.58ml of concentrated hydrochloric acid in 1000ml water) solution and shaking intermittently for one hour. The hydrochloric acid solution was standardised by using 0.1N sodium carbonate (5.3g in 1000ml). The suspension was allowed to settle for one hour and 10ml of the supernatant solution was pipetted out and titrated with 0.1N sodium hydroxide (4g in 1000ml). The sodium hydroxide was standardised using 0.1N potassium hydrogen phthalate (2.042g in 100ml). Bromo cresol purple (0.025 g of Bromo Cresol

Purple indicator dissolved in 125 ml of alcohol) was used as the indicator (Jackson, 1958).

$$EB = \frac{[100- (\text{titer value} \times 10)] \times 0.1 \times 100]}{\text{Sample weight}}$$

4.2.3. Exchangeable sodium and potassium

Exchangeable sodium and potassium were extracted with 1N neutral ammonium acetate solution (77.09g ammonium acetate in 20L of distilled water and pH adjusted to 7 by addition of either ammonia or acetic acid). To five gram of soil, 25ml of 1N ammonium acetate was added, shaken for five minutes and filtered through Whatman No. 1 filter paper. The extract, thus, obtained was used for the determination of exchangeable sodium and potassium by using a Flame photometer (ELICO CL 361) (Jackson, 1958).

Standard sodium chloride solutions of 5, 10, 20, 40 and 60 ppm for sodium and standard potassium chloride solutions of 5, 10, 20, 30 and 40 ppm for potassium were prepared. In order to prepare 1000ppm primary standard sodium chloride solution, 2.5418g pure dry sodium chloride was dissolved in 1000ml distilled water. From this 5, 10, 2, 30 and 40ppm standard solutions were prepared by appropriate dilutions.

The standard potassium chloride solutions were prepared, first by preparing 1000ppm primary standard solution by dissolving 1.9090g pure dry potassium chloride in 1000ml distilled water and from this primary standard, 5, 10, 20, 30 and 40ppm standard solutions were prepared by appropriate dilutions. The absorbance of standard solutions of sodium and potassium was measured and respective standard curves prepared. From the standard curves, the amount of sodium and potassium in the aliquot and subsequently in the sample was calculated.

$$\text{Exchangeable sodium/potassium in soil} = \frac{X \times 25 \times 10^6}{5 \times 10^6}$$

where X = Amount of potassium/sodium in the extract

4.2.4. Exchangeable calcium and magnesium

To five gram of soil, 25ml of 1N ammonium acetate was added, shaken for five minutes and filtered through Whatman No. 1 filter paper. From the extract thus obtained, Exchangeable sodium and potassium was determined by titrating with EDTA. (Hesse, 1971). To five ml of ammonium acetate extract, ten drops each of potassium cyanide (1g in 100ml), hydroxyl ammine hydrochloride (5g in 100ml) and triethanol ammine (20 mg in 50ml methanol) were added, followed by 1-2 ml of of 10% sodium hydroxide to raise the pH to 12 or slightly higher. To this, five drops of calcon indicator was added and titrated against standard 0.01 N EDTA solution (2.0g of EDTA disodium salt in 1000ml distilled water). From the titer value so obtained, exchangeable calcium content in soil was calculated. EDTA was standardised using 0.01N calcium chloride as a primary standard [0.50g of oven dried calcium carbonate dissolved in minimum excess of dil. hydrochloric acid (240ml of concentrated hydrochloric acid in 1000ml water) and made up to 1000ml].

To estimate the quantity of calcium and magnesium in 5ml of aliquot, 15ml ammonium chloride - ammonium hydroxide buffer [67.5g of pure ammonium chloride in 570ml of concentrated ammonium hydroxide (precooled) made up to 1000ml with water], and ten drops each of potassium cyanide (1g in 100ml), hydroxyl ammine hydrochloride (5g in 100ml), potassium hexacyanoferrate (II) (3.5g in 100ml) and triethanol ammine solutions (20mg in 50ml methanol) were added and warmed gently on a magnetic stirrer. After cooling ten drops of Erichrome Black T was added to it and titrated with standardized 0.01N EDTA solution. From the titer value, calcium and magnesium content in aliquot was calculated. Magnesium was determined by subtracting the amount of calcium from the amount of calcium and magnesium in aliquot.

Ex. Ca in soil = Titer value x 0.02 x 10^4

Ex. Mg in soil = (Titer value of Ca & Mg - Titer value of Ca) x 0.012 x 10^4

4.2.5. Available phosphorus

Available phosphorus was extracted using Bray's No.1 extractant (0.03N ammonium flouride + 0.025N hydrochloric acid) (Bray and Kurtz, 1945) and phosphorus content determined spectrophotometrically by ascorbic acid reduced molybdophosphoric blue colour method (Watanabe and Olsen, 1965). To prepare the standard curve, 100ppm stock solution of phosphorus was prepared by dissolving 0.493g of dihydrogen orthophosphate in half a liter of distilled water. From this 100ppm stock solution, standard solutions of 1, 3, 5, 10 and 15ppm were prepared by appropriate dilutions. The soil extract was prepared by shaking 5g of soil with 50ml of Bray's No.1 extractant and filtered with No. 42 filter paper. The solution was refiltered with activated charcoal. Five ml of extractant was pipetted into 25ml volumetric flask and carefully acidified with 5N sulphuric acid to pH 5. (The 5N sulphuric acid was prepared by dissolving 140ml concentrated sulphuric acid in one litre distilled water.) Added 7.5 ml of boric acid (50g in 1000ml) to prevent interference with fluorine and four ml of coloring reagent and the volume made up to mark. The colouring reagent was prepared by dissolving ascorbic acid (1.056g) in antimony potassium tartarate and ammonium molybdate solution (12g of ammonium molybdate was dissolved in 250ml of distilled water and 0.297g of antimony potassium tartarate was dissolved. in 100ml of distilled water, separately. Both these solutions were added to 2000ml of volumetric flask, mixed thoroughly and made up to the mark). After waiting for 10 minutes, the blue colour developed was read at 660nm. The process was repeated with standard phosphorus solution of varying concentrations to prepare a standard curve. From the standard curve, concentration of phosphorus in the extract was read.

Av. P in soil = X x 10

Where X = ppm of phosphorus in aliquot

4.2.6. Organic carbon

The organic carbon in soil was determined colorimetrically by the method described by Sree Ramulu (2003). Air dried and sieved (0.2mm mesh size) soil (0.5g) was transferred into a dry 100ml conical flask. To this, 10ml of 1N potassium dichromate was added followed by followed by 20ml of concentrated sulphuric acid at a stretch. (The 1N potassium dichromate solution was prepared by dissolving 49.04 g of potassium dichromate in 1000ml water.) This solution was allowed to stand on an asbestos pad for 30 minutes and then 70ml of distilled water was added to it. The intensity of green colour of chromium sulphate formed was measured in a spectrophotometer at 660nm. Standard solutions for caliberation curve were prepared from anhydrous sucrose. In order to prepare standard caliberation curve, 2000ppm standard stock solution was prepared by dissolving 1.0008g accurately weighed anahydrous sucrose in 200ml distilled water. From this stock solution, 2, 5, 15 and 25ml were pipetted out seperately into different conical flasks and evaporated to dryness by placing overnight in an oven at 105^{0} C. (Care was taken not to overheat or burn the flask.) To this flask, 10ml of 1N potassium dichromate was added followed by 20ml of concentrated sulphuric acid at a stretch. This solution was allowed to stand on an asbestos pad for 30 minutes and then 70ml of distilled water was added to it. This is equivalent to 40 (for 2ml), 100 (for 5ml), 300 (for 15ml) and 500ppm (for 25ml) standard solutions. The intensity of green colour of chromium sulphate formed was measured in a spectrophotometer at 660nm and standard cuvre generated. From the standard curve, organic carbon content in the sample was calculated.

Per cent of O.C in soil = X/50

where X = ppm of carbon in aliquot.

4.2.7. Total nitrogen

As it is envisaged to find out the organic carbon: nitrogen ratio, the total nitrogen content in the soil was found out for arriving at this ratio. Total nitrogen was estimated by Kjeldahl method as described in Jackson (1958). To 0.5g of soil, 4 ml of sulphuric acid - salicylic acid mixture was added and kept aside for 30 minutes. (The sulphuric acid-salicylic acid mixture was prepared by dissolving 2.5g salicylic acid in 100ml concentrated sulphuric acid.) To the soil-acid mixture, 0.5g sodium thoisulphate was added and heated for five minutes. The flask was then allowed to cool and 1.1g of potassium sulphate catalyst mixture added and the flask heated until the digestion completed. (The catalyst mixture was prepared by grinding 20g of potassium sulphate, 5g of cupric sulphate pentahydrate and 0.5g of selenium powder). The flask was allowed to cool and contents of the flask transferred completely to a Kjeldahl's flask by washing with distilled water. After setting up the distillation apparatus, 10N sodium hydroxide (400g in 1000ml) was added to the flask and the ammonia liberated was collected by dissolving in two per cent boric acid containing the mixed indicator (bromocresol green and methyl red). The nitrogen was estimated by titrating against standard sulphuric acid. In order to standardize sulphuric acid, 1.06g of sodium carbonate was dissolved in water and diluted to one liter. This is 0.02N sodium carbonate solution. From the sodium carbonate solution, 10ml was pipetted into a beaker and two drops of mixed indicator (0.066g methyl red and 0.099g bromocresol green in 100ml ethyl alcohol) added and titrated agaist sulphuric acid and normality of sulphuric acid calculated.

$$\text{Total Nitrogen} = \frac{(\text{Titer value})*14*(\text{Normality of sulphuric acid})*100*50}{1000*0.5*20}$$

4.2.8. Statistical analysis

From the data, both mean values and relative mean values were calculated. In order to calculate the relative mean values, the mean values of control stand i.e. natural forest was assigned a value of hundred and the relative mean of plantations was calculated as

Relative mean = (mean of plantation x 100)/mean of natural forest)

It was thus possible to compare soils in plantations in different locations (Mishra *et al.*, 2003).

ANOVA was done for each location and for each depth level separately for comparing between vegetation. To study the soil changes over time, ANOVA was done for each age class and depth level. If the analysis of variance was found to be significant, Least Significant Difference was used for pair wise comparison. The analysis was carried out using SPSS software package (Norusis, 1988).

4.3. Results and Discussion

The mean values of soil chemical properties in plantations of teak and natural forest are depicted in Table 4 and those of eucalypt and natural forest are given in Table 5. Analysis of variance of soil properties (ANOVA) due to vegetation type are presented in Appendices 26 to 37. ANOVA between soils of natural forest and different age class teak plantations and those of the natural forest and different rotation eucalypt plantations are given in Appendices 37 to 50.

4.3.1. Soil pH

4.3.1.1. Teak

Soils of both teak plantations and natural forest were moderately to strongly acidic in nature. Plantations of younger age class teak and natural forest had similar mean soil pH values. The same was noted by Okoro *et al.* (1999, 2000) and Chamshama *et al.* (2000) in a single age teak plantation and adjacent natural forest. However, soils of older teak plantations had significantly higher pH values than those in natural forest in all the three depths. Within teak plantations, relative mean pH values were found to increase with age in all depths. Higher pH values in soils of single age teak plantations compared to natural forest was also observed by Nath *et al.* (1988) and Balagopalan and Jose (1993, 1997).

4.3.1.2. Eucalypts

Soils in eucalypt plantations were moderately acidic while that of natural forest were slightly acidic. A significant lowering of soil pH values was observed in eucalypts relative to natural forest in all the three depths. This is in agreement with the findings of Purwanto (1990) and Balagopalan (1992). It was observed that soil pH values decreased with rotation in plantations of eucalypt and the decrease was significant in the lowest depth. This corroborates the findings of Balagopalan (1992, 1995b).

4.3.1.3. Comparative evaluation

Change in soil pH values due to monoculture plantations depend on intrinsic pH of the soil and type of tree species growing on the site (Moran *et al.*, 2000). When soils in

Table 4. Mean values of soil chemical properties in natural forest and teak plantations

Study area	Location	Vegetation types	Age class	Depth --cm--	Chemical Properties									
					pH	Ex. Bases	Ex. Na	Ex. K	Ex. Ca	Ex. Mg	Av. P	O.C	Total N	C/N
						%	---ppm---					---%---		
Vazhachal Forest Division	Site I Karadipara	Natural forest	-	0-20	5.4	6.8	4	5	254	117	1.2	2.6	0.29	9.0
				20-40	5.3	4.4	4	7	208	44	0.6	1.8	0.23	9.3
				40-60	5.2	4.6	4	7	188	62	0.7	1.5	0.16	9.2
				0-60	5.3	5.3	4	6	217	74	0.8	2.0	0.23	9.2
		Teak	21-30Y	0-20	5.2	6.2	4	3	280	104	0.8	1.5	0.28	6.0
				20-40	5.2	6.4	4	5	212	106	0.5	1.1	0.16	7.4
				40-60	5.3	5.0	4	4	224	77	0.3	1.0	0.19	5.6
				0-60	5.2	5.9	4	4	239	96	0.5	1.2	0.21	6.4
			31-40Y	0-20	5.4	6.3	4	4	367	99	2.7	1.4	0.28	5.0
				20-40	5.3	5.7	4	7	234	89	0.7	0.8	0.22	4.1
				40-60	5.4	6.0	4	7	260	76	0.2	0.7	0.18	4.3
				0-60	5.4	6.0	4	6	287	88	1.2	0.9	0.22	4.5
	Site II Athirapilly	Natural forest	-	0-20	4.6	6.8	6	10	352	151	1.9	2.7	0.33	8.3
				20-40	4.7	8.8	4	12	308	134	1.3	1.7	0.22	7.7
				40-60	4.7	8.4	4	11	296	138	1.7	1.3	0.14	8.9
				0-60	4.7	8.0	5	11	319	141	1.7	1.91	0.23	8.3
		Teak	41-50Y	0-20	4.9	8.0	6	8	392	128	1.6	2.3	0.34	7.7
				20-40	5.0	7.6	6	7	240	95	0.6	1.5	0.22	6.9
				40-60	5.1	7.2	6	5	232	62	0.6	1.2	0.17	7.2
				0-60	5.0	7.6	6	6	279	95	1.0	1.6	0.25	7.2
			>50Y	0-20	5.1	9.1	8	6	376	134	1.9	2.2	0.34	6.8
				20-40	5.1	8.8	9	3	284	113	1.0	1.6	0.26	6.1
				40-60	5.0	11.3	9	3	320	114	0.7	1.23	0.19	6.2
				0-60	5.1	9.7	9	4	327	120	1.2	1.7	0.27	6.4

Table 5. Mean values of soil chemical properties in natural forest and eucalypt plantations

Study area	Location	Vegetation types	Rotation	Depth	Chemical Properties and Macronutrient									
				--cm--	pH	Ex. Bases	Ex. Na	Ex. K	Ex. Ca	Ex. Mg	Av P	O.C	Total N	C/N
						%	---ppm---					---%---		
Thrissur Forest Division	Marotichal	Natural forest	-	0-20	6.5	37	21	25	1848	530	3	4.26	0.33	11.3
				20-40	6.3	28	21	25	1124	365	2	2.88	0.29	8.5
				40-60	6.1	21	23	13	672	382	2	1.42	0.19	6.2
				0-60	6.3	29	22	21	1215	426	2	2.85	0.27	8.7
		Eucalypt	Rotation 2 coppiced	0-20	5.7	28	18	24	704	587	6	2.58	0.23	11.1
				20-40	5.6	25	22	18	404	492	4	1.75	0.14	12.5
				40-60	5.8	24	30	16	536	655	4	1.37	0.15	9.4
				0-60	5.7	25	23	19	548	578	5	1.90	0.17	11.0
			Rotation 3 coppiced	0-20	5.6	23	47	15	604	334	8	1.97	0.12	13.7
				20-40	5.5	17	45	14	392	293	7	1.32	0.09	14.3
				40-60	5.4	23	51	11	416	302	5	0.93	0.14	8.5
				0-60	5.5	21	47	13	471	310	7	1.41	0.12	12.1
			Rotation 3 replanted	0-20	5.4	19	59	24	460	151	9	2.66	0.19	14.0
				20-40	5.5	25	59	17	484	130	8	1.91	0.12	15.6
				40-60	5.5	18	58	17	436	156	11	1.34	0.096	13.9
				0-60	5.4	21	59	19	460	146	9	1.97	0.14	14.5

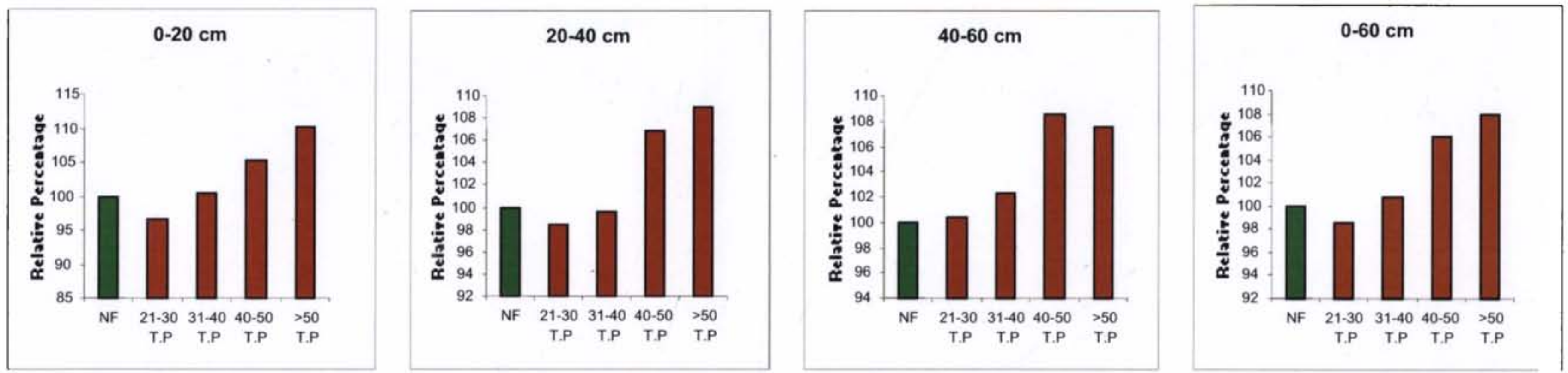

Fig.12 Relative mean values of soil pH at different depths in natural forest and teak plantations.

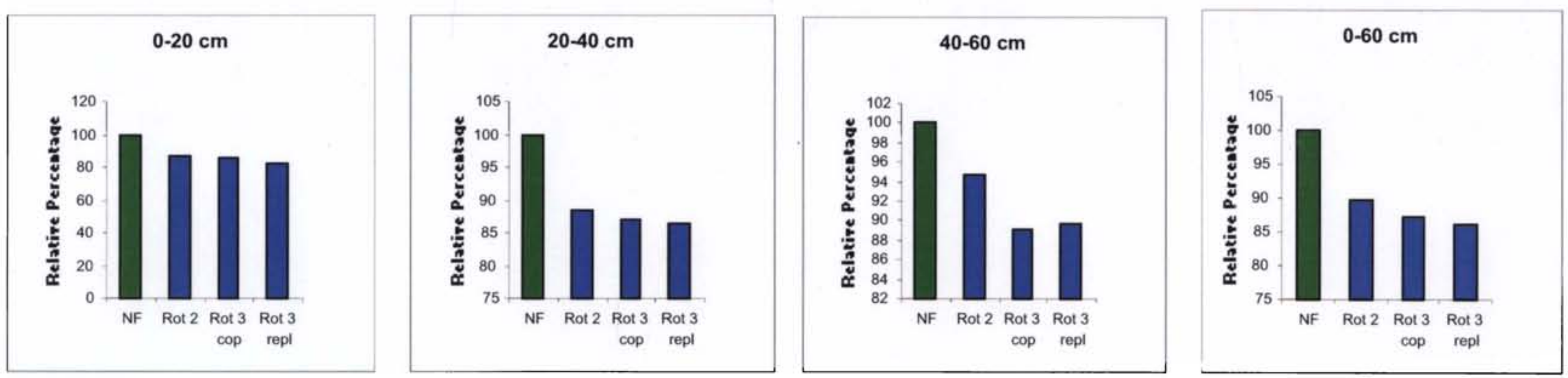

Fig.13 Relative mean values of soil pH at different depths in natural forest and eucalypt plantations.

natural forest, teak and eucalypt were compared, it was observed that plantation activity changed soil pH. Soils in teak showed an increase in soil pH values while those in eucalypts recorded a decrease in pH values. This could be due to the fact that deciduous trees tend to add more bases to the soil (Balagopalan and Jose, 1982b). Teak being deciduous in nature, soils in teak had relatively higher pH values. Similar results have also been reported by Marquez *et al.* (1993).

In the case of eucalypt plantations, such process is non existent and the only factor that influence the soil acidity is the leaching of bases (Balagopalan and Jose, 1983). Soil pH values decreased with rotation in eucalypt plantations and the decrease was significant in the lowest depth. Similar findings were reported by Balagopalan and Jose (1983) and Balagopalan (1995a). Among these plantations as third rotation plantations were exposed to vagaries of nature most often the leaching loss from soil would be correspondingly higher, leading to a greater decline in pH values. When soils under teak and eucalypts for similar periods (up to 40Y) were considered, it was observed that the greatest variation in soil pH was under eucalypts. No significant difference was observed between soils of teak plantations and natural forest regarding soil pH.

4.3.2. Exchangeable bases

4.3.2.1. Teak

Exchangeable bases contents varied from 3 to 12 per cent in soils of natural forest while in plantations, the values ranged from 2 to 15 per cent. In the 0-20cm depth, no significant difference was observed between plantations of teak and natural forest. The mean values varied from 6.2 to 9.1 per cent in plantations of teak. Among teak plantations, an increase in the value of mean exchangeable bases was observed with age. The relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 91, 92, 118 and 134 per cent, respectively. Close exchangeable base values in soils of natural forest and an adjacent teak plantation was recorded by Balagopalan (1995b).

In the 20-40cm depth, no significant difference was observed between soils of natural forest and teak plantations. The relative mean values in 21-30Y, 31-40Y, 41-50Y and

>50Y age class plantations were 145, 130, 86 and 100 per cent, respectively. The mean values varied from 5.7 to 8.8 per cent.

In the 40-60cm depth, the mean values were in the range of 5 to11.3 per cent. A significant increase in exchangeable base values was observed in >50Y age class plantation. The relative mean values of 21-30Y, 31-40Y, 41-50Y and >50Y age class were 109, 130, 86 and 135 per cent, respectively.

In the 0-60cm depth, mean values in natural forest and plantations were very close and did not differ significantly from each other. Balagopalan (1995a) also observed similar values for exchangeable bases in a teak plantation and adjacent moist deciduous forest. No definite pattern of variation with age was observed, in this depth, among plantations of teak. The mean values of exchangeable bases, in plantations of teak, lay between 5.9 to 9.7 per cent. The relative mean exchangeable bases in plantations of 21-30Y, 31-40Y, 41-50Y and >50Y age classes were 111, 113, 95 and 122 per cent, respectively.

4.3.2.2. Eucalypts

The highest value for exchangeable bases was observed in the 0-20cm depth in natural forest and second rotation eucalypt plantations. The exchangeable bases in natural forest were in the range of 17 to 40 per cent while in eucalypts, the values varied from 13 to 37 per cent.

The mean values of exchangeable bases, in the 0-60cm depth, in plantations ranged from 21 to 25 per cent. The exchangeable bases in plantations were significantly lower than those in the natural forest and decreased with rotation. The same pattern was also observed in the 0-20cm depth. Soils in plantations had significantly lower exchangeable bases than natural forest and the values decreased significantly with rotation. Mean values ranged from 19-28 per cent. Exchangeable bases in replanted plantation were lower than those of coppiced one. The relative mean values of exchangeable bases in second rotation, third rotation coppiced and third rotation replanted plantations were 89, 75 and 72 per cent, respectively in the 0-60cm depth while corresponding values in the 0-20cm depth were 74, 63 and 50 per cent. On comparing the soils of uncoppiced, I and II

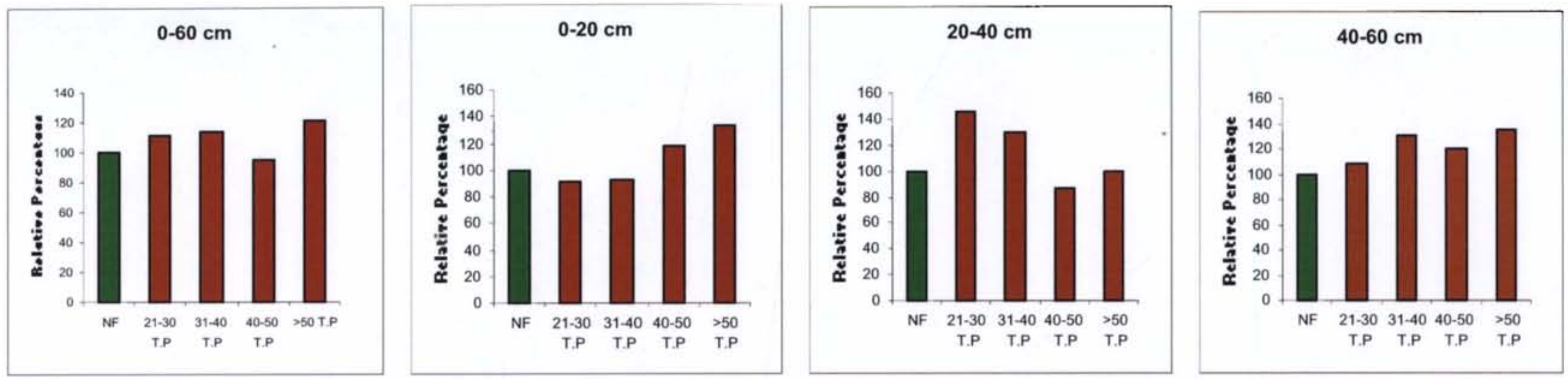

Fig.14. Relative mean values of exchangeable bases at different depths in natural forest and teak plantations.

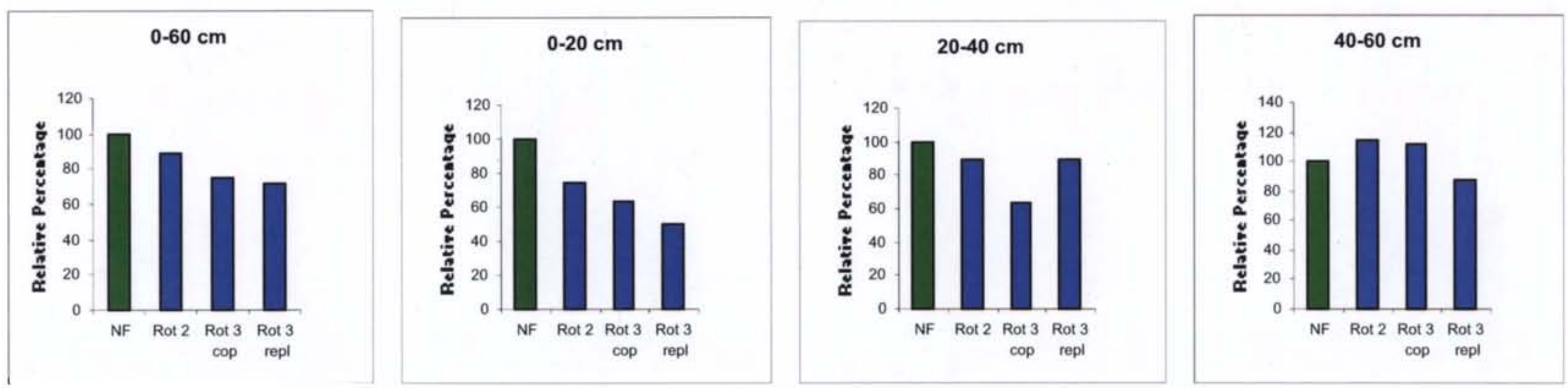

Fig.15. Relative mean values of exchangeable bases at different depths in natural forest and eucalypt plantations.

coppiced plantations of eucalypt, Balagopalan (1995b) also observed the same pattern of variation in the 0-20cm depth. In the 20-40cm depth, exchangeable bases contents in eucalypts plantations were lower than those in the natural forest and the difference was significant in third rotation coppiced plantation. Exchangeable bases in soils of replanted plantations were greater than coppiced one. This may be due to fertilizer application in replanted plantations during the initial years of plantation establishment. The mean values of exchangeable bases in 20-40cm depth varied from 17 to 25 per cent while in 40-60cm depth, the values ranged from 18 to 24 per cent. There was no significant difference in exchangeable bases contents between natural forest and plantations in the 40-60cm depth. The relative mean values for second rotation, third rotation coppiced and third rotation replanted plantations were 90, 63 and 90 per cent, respectively in the 20-40cm depth while, corresponding values in the 40-60cm depth were 114, 112 and 86 per cent.

4.3.2.3. Comparative evaluation

When exchangeable bases contents in soils of teak and eucalypt plantations and natural forest were compared, a significant decline was noticed in eucalypt plantations in the 0-20cm depth. In the 0-60cm depth, a significant decline from natural forest values was observed in third rotation eucalypt plantations. Teak soils, on the other hand, exhibited no significant difference.

When soils, under plantations of teak and eucalypts, over similar time scale were compared, it was observed that loss of exchangeable bases from plantation soils was greater in eucalypts than in teak. The loss of exchangeable bases was significant in eucalypts while in teak, this was not significant. During the 21-30Y period, in the 0-20cm depth, there was a loss of nine per cent in teak plantations while in eucalypts, the loss was 26 per cent. In the 31-40 year period, an eight per cent loss of exchangeable bases was recorded in teak even as soils under eucalypts suffered losses varying from 38 to 50 per cent.

4.3.3. Exchangeable Sodium

4.3.3.1. Teak

The amount of exchangeable sodium in soils was low in both natural forest and teak plantations. In natural forest, it was in the range of four to nine ppm whereas in teak plantations it varied from 4 to 15ppm. No definite relationship between exchangeable sodium and depth was noticed.

Sodium contents in soils of natural forest and younger age class plantations, in the 0-60cm depth, were very close. In older teak plantations, the values were slightly higher than those of natural forest and the difference, though small, was significant in oldest teak plantations. A similar pattern of change was observed in the 0-20, 20-40 and 40-60cm depths. The relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations in the 0-60cm depth were 100, 99, 132 and 181 per cent, while in the 0-20cm depth, the values were 102, 99, 111 and 138 per cent, respectively. The mean values varied from four to nine ppm in the 0-60cm depth and from four to eight ppm in 0-20cm depth. There was no significant difference in the soils of 0-20 cm depth with respect to sodium between teak plantations and natural forest.

The relative mean values for exchangeable sodium in the 20-40cm depth of 21-30Y, 31-40Y, 41-50Y and >50Y age class teak plantations were 100, 100, 142 and 193 per cent, respectively. In the 40-60cm depth, the corresponding values were 97, 96, 149 and 225 per cent. The mean values for exchangeable sodium in plantations of teak were in the range of four to nine ppm in both 20-40 and 40-60cm depth. In the oldest age class teak plantation, a slight and significant increase in soil exchangeable sodium was observed in 20-40 and 40-60cm depths.

4.3.3.2. Eucalypts

In the natural forest, the amount of exchangeable sodium varied between 11 to 29ppm, while, in plantations of eucalypts, the exchangeable sodium contents ranged from 10 to 90ppm.

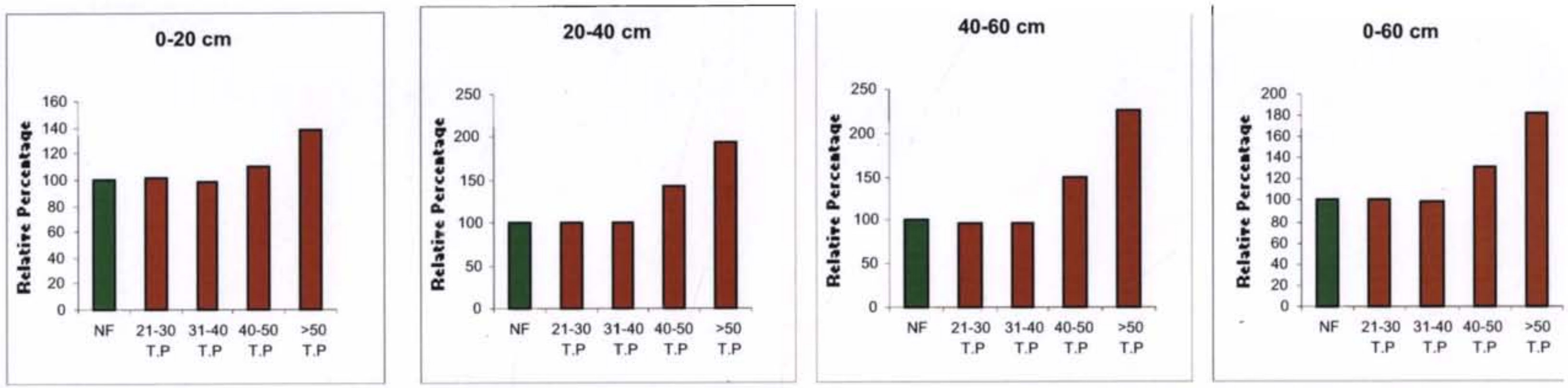

Fig.16 Relative mean values of exchangeable sodium at different depths in natural forest and teak plantations.

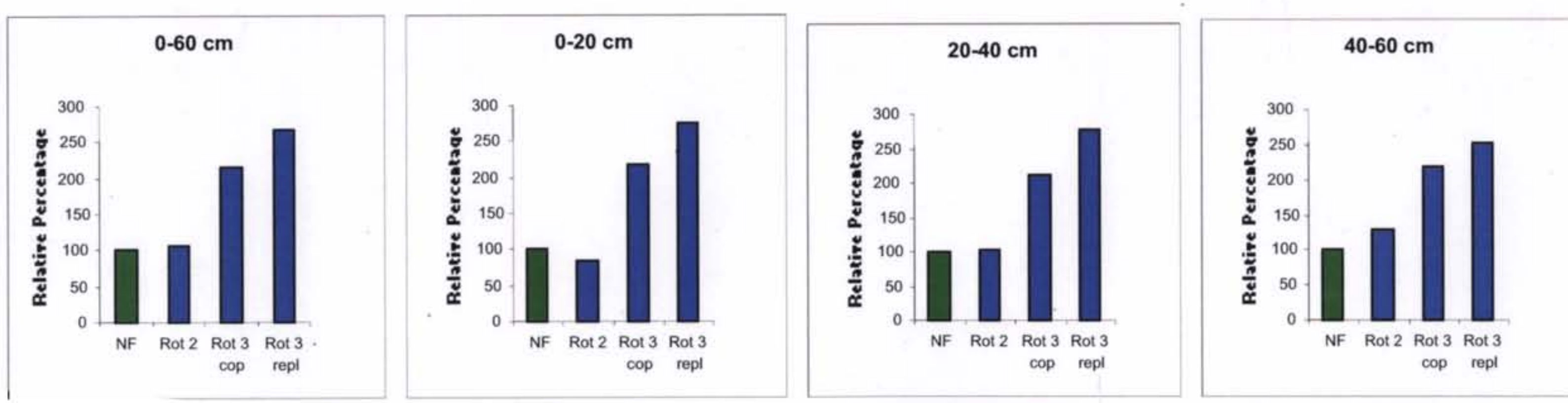

Fig.17 Relative mean values of exchangeable sodium at different depths in natural forest and eucalypt plantations

The amount of exchangeable sodium in the 0-60cm depth in natural forest and second rotation plantations of eucalypts were very close while in third rotation plantations, the values were significantly higher. Among third rotation plantations, higher values for exchangeable sodium were seen in replanted plantations than coppiced ones. The same trend was also observed in the 0-20cm, 20-40cm and 40-60cm depths. The mean values of exchangeable sodium in the 0-60cm depth of eucalypts plantations were in the range of 23 to 59ppm and the relative mean values for second rotation, third rotation coppiced and third rotation replanted plantations were 106, 217 and 269 per cent, respectively. In the 0-20cm soil depth of the aforesaid plantations, mean values varied from 18 to 59ppm and the relative mean values for the above plantations were 86, 219 and 277ppm. No significant difference was observed in the amount of exchangeable sodium between natural forest and second rotation eucalypts. On the other hand, soils in third rotation plantations had significantly higher amount of exchangeable sodium than that of natural forest.

When the exchangeable sodium in the 20-40cm and 40-60cm depths were determined, the mean values for second rotation, third rotation and third rotation replanted plantations were between 22 to 59ppm and 30 to 58ppm, respectively. The relative mean values were 102, 222 and 278 per cent in the 20-40cm depth and 129, 220 and 253 per cent in the 40-60cm depth. At both these depths, exchangeable sodium in second rotation eucalypt plantations showed no significant difference from natural forest whereas in third rotation plantations the increase was significant.

4.3.3.3. Comparative evaluation

The effect of eucalypt plantations on exchangeable sodium in soils was more pronounced than that in teak. When soils under plantations for similar period of time were considered, it was seen that during the 20 to 30 year period, both the plantations were similar to natural forest. However after 30 to 40 years, the amount of exchangeable sodium in eucalypt plantations was much higher than that of natural forest. This drastic increase was not seen in plantations of teak. Higher amount of exchangeable sodium in soils of eucalypt compared to teak was also reported by Chavan *et al.* (1995).

4.3.4. Exchangeable potassium

4.3.4.1. Teak

No significant difference was observed between soils of younger teak plantations and natural forest with respect to the amount of exchangeable potassium. In contrast, a small but significant decrease was observed when soils of older teak plantations and natural forest were compared.

In the 0-60cm depth, the relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y plantations of teak were 68, 95, 59 and 39 per cent, respectively whereas in the 0-20cm depth, corresponding values were 68, 77, 79 and 63 per cent. In the 20-40 and 40-60cm depths, the relative mean values for plantations of these age classes were 78, 101, 56 and 28 per cent and 66, 101, 44 and 29 per cent, respectively.

Among plantations of teak, lower relative mean values for potassium were observed in older plantations with the lowest value being recorded in the oldest age class. It was also noticed that potassium in soils initially increased and then decreased marginally with age. This pattern was observed in all the three depths. It has been reported that leaf in younger plantations accumulate higher quantities of minerals than older plantations (Sonkar 2004). These nutrients are available for recycling and their continuous addition and decomposition may enrich the soil. This translates into higher close quantity of potassium in the soils of younger teak plantations and natural forest. As teak stand ages, a decrease in net leaf biomass results in lowered nutrient return to soil (Karmacharya and Singh, 1992). This is accompanied by an increase in root biomass. As maximum potassium, in teak is held up in roots, an increase in root biomass progressively removes this potassium from circulation (Negi *et al.*, 1990, Negi *et al.*, 1995). These factors were responsible for the lower exchangeable potassium seen in older plantations.

In the 0-20cm depth where the influence of litter is most pronounced, the difference between younger and older plantations was less, where as in the 20-40 and 40-60cm depth, the difference was more evident. Soils in the 0-20cm depth of the oldest teak plantation differed significantly from natural forest. On the other hand, in the 20-40 and

40-60cm depths, the difference was significant in both the older teak plantations. In the 0-60cm depth, a significant lowering of exchangeable potassium values was observed in older plantations of teak. Aborisade and Aweto (1990), Mongia and Bandyopadhyay (1994), Balagopalan and Jose (1993), Balagopalan (1995a, 1995b) and Amponsah and Meyer (2000) observed lower exchangeable potassium in plantation soils compared to natural forest.

4.3.4.2. Eucalypts

The mean value of exchangeable potassium in the 0-60cm depth in natural forest is 21ppm while in plantations of eucalypt, the values varied from 13 to 19ppm. The relative mean values for second rotation, third rotation coppiced and third rotation replanted plantation were 93, 63 and 92 per cent, respectively. The mean values in natural forest in the 0-20, 20-40 and 40-60cm depths were 25, 25 and 13ppm, respectively. The relative mean values in the second rotation, third rotation coppiced and third rotation replanted plantations were 96, 60 and 94 per cent, respectively in the 0-20cm depth while corresponding values in the 20-40 and 40-60cm depths were 72, 55 and 68 per cent and 130, 84 and 136 per cent.

Exchangeable potassium in plantations of eucalypt decreased marginally with rotation. The mean values of exchangeable potassium in third rotation coppiced plantation were lower than those in the natural forest and second rotation plantation. The decrease from natural forest, though small, was significant in third rotation coppiced plantation in the 20-40cm depth. On the other hand, replanted third rotation and second rotation plantations had similar amount of exchangeable potassium. The loss of potassium from soils owing to plantation activity was visible in the third rotation coppiced plantation. The increase in exchangeable potassium in replanted third rotation plantation may be attributed to the addition of fertilizers during the initial years of plantation establishment. This trend was seen in both 0-20cm and 20-40cm soil depths and also in the 0-60cm depth. Sunita and Uma (1993), Bargali *et al.* (1993), Balagopalan and Jose (1993) and Balagopalan (1995b) reported lower potassium content in eucalypt soils compared to natural forest.

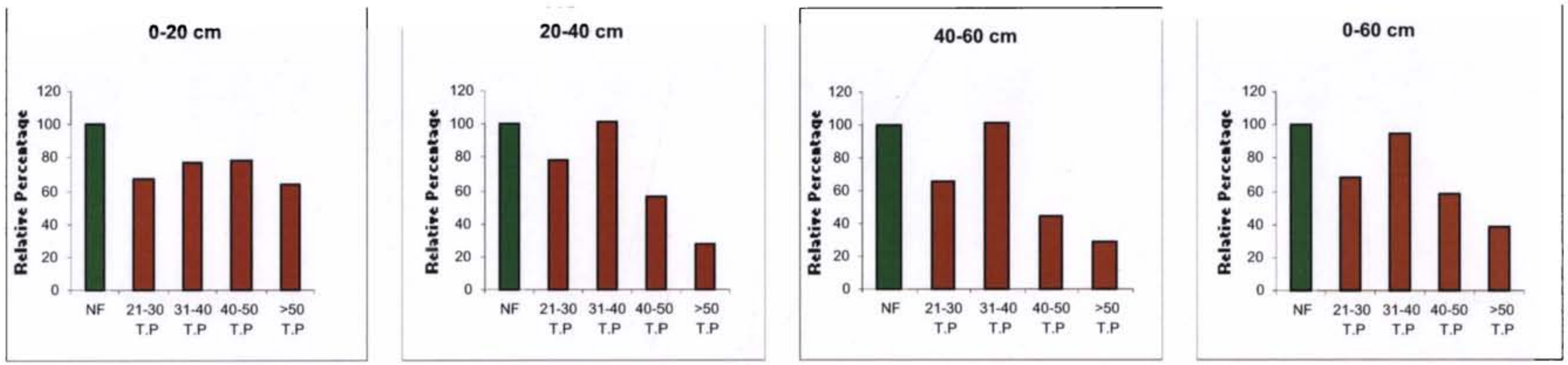

Fig.18 Relative mean values of exchangeable potassium at different depths in natural forest and teak plantations.

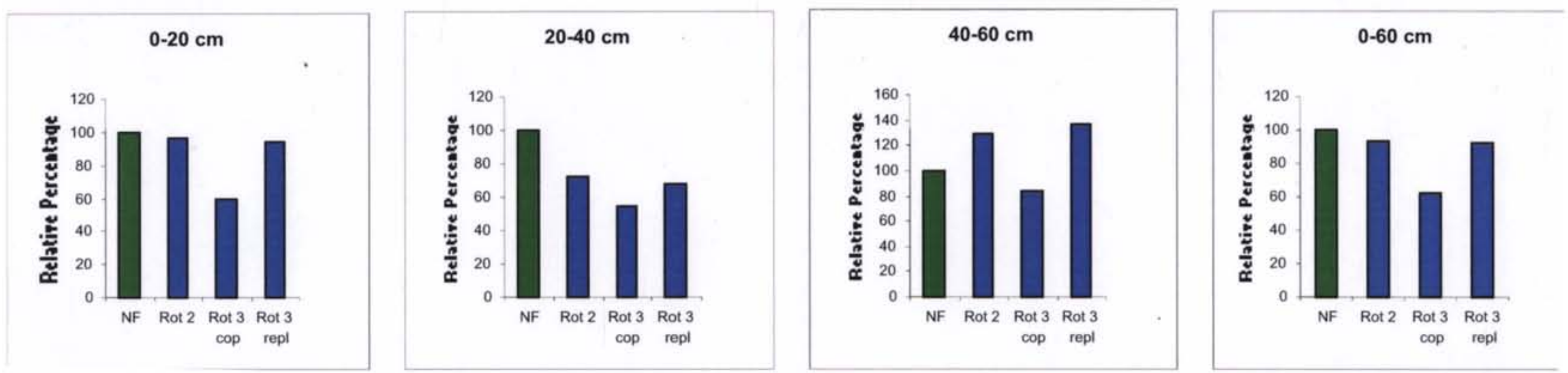

Fig.19 Relative mean values of exchangeable potassium at different depths in natural forest and eucalypt plantations.

4.3.4.3. Comparative evaluation

When the exchangeable potassium in plantation soils were compared to that of natural forest, a notable difference was seen only in older teak plantations. On comparing soils under plantations of teak and eucalypts for 20 to 30 years, no outstanding difference was noticed. but when soils under monoculture for 30 to 40 year were compared, a greater decline in the exchangeable potassium was observed in plantations of eucalypt (especially coppiced) than teak. The difference from natural forest was significant only in coppiced plantation. On the whole, plantation activity does not seem to have a pronounced affect on potassium content of plantation soil. Singh *et al.* (1990) noted that exchangeable potassium in 44-54Y old teak plantation was lower than that of 18-20Y old eucalypt.

The lowering of relative mean value in the 0-60cm depth in teak plantations was five per cent while in coppiced eucalypt plantations, it was 37 per cent and in replanted eucalypt plantations, it was eight per cent. In the 0-20cm depth, the relative lowering in teak plantations was 23 per cent while in coppiced and replanted eucalypt plantations, it was 40 and 5 per cent, respectively. The relative mean values in the 20-40cm depth in teak plantations was similar to those in the natural forest but in coppiced and replanted eucalypt plantations. the values were lower than natural forest by 46 per cent and 32 per cent, respectively.

4.3.5. Exchangeable Calcium

4.3.5.1. Teak

In soils of natural forest, calcium content decreased with depth. In plantations of teak, higher values for exchangeable calcium was observed in the surface layer though a steady decline with depth was not observed. The values in the natural forest were in the range of 120 to 410ppm and in teak plantations, the values lay between 160 to 480ppm. Among teak plantations. highest relative mean value was recorded in 31-40Y age class plantations.

A comparison of soils in the natural forest and plantations, in the 0-20cm depth, led to the conclusion that exchangeable calcium was higher in plantations than natural forest. It was also observed that the values initially increased and then decreased with the age of the plantations. The mean values of teak varied from 280 to 392ppm and the relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 110, 145, 111 and 107 per cent, respectively. The highest relative mean value was observed in the 31-40Y age class plantations and the increase from natural forest was significant. On comparing with adjacent natural forest, higher calcium content in a plantation of teak was reported by Rathod and Devar (2003b).

Higher amount of exchangeable calcium in younger plantations compared to older plantations was also observed in 20-40 and 40-60cm depths. The mean values for various age classes in these depths varied from 212 to 284ppm and from 224 to 320ppm, respectively. The relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 102, 113, 78 and 92 per cent and 119, 138, 78 and 108 per cent, respectively.

On studying the soils in the 0-60cm depth, it was observed that calcium content was higher in younger than in older plantations. No significant difference was observed between soils of plantations and natural forest. The mean values in this depth varied from 239 to 327ppm. The relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age classes teak plantations were 110, 135, 82 and 96 per cent, respectively. Balagopalan (1995a) observed that exchangeable calcium values in a 21-30Y age class teak plantation did not differ significantly from that of adjacent natural forest. Contrary to this, Aborisade and Aweto (1990), Okoro *et al.* (1999) and Amponsah and Meyer (2000) noted lower exchangeable calcium in teak soils.

The higher availability of calcium in soils of plantations than natural forest, in the 0-20cm depth, may be attributed to the influence of teak leaf litter. Teak litter is known to be rich in calcium. It also accumulates in greater quantities in the foliage than other cations and does not go out of the foliage just before leaf fall as large portion of other elements do (Banerjee and Badola, 1980). Thus, the surface soil became richer in calcium by leaf fall followed by its decomposition and release of nutrients like calcium.

In younger plantations, accumulation of the mineral, in leaf, is high (Negi *et al.*, 1995). These nutrients are available for recycling and their continuous addition and decomposition enriches the uppermost layer. In older plantations, the biomass of non photosynthetic components increases and the major portion of all the nutrients are accumulated in bole while the maximum calcium is held up in bark (Negi *et al.*, 1990; Negi *et al.*, 1995 and Nwoboshi, 1984). Also leaf biomass decreases with age of the stand (Karmacharya and Singh, 1992). Correspondingly, nutrients returned to the soil via litter decreases. Accumulation of calcium in trees also increases with tree age as they absorb calcium from the soil which is immobilized in cell walls (Binkley, 1986). These nutrients are removed from the cycle which eventually translates into lower exchangeable calcium in older plantations *viz.*, 41-50Y and >50Y age classes. The 20-40 and 40-60cm depths are not directly affected by litter. Though there may be downward movement of ions, this pattern of variation is not clearly discernable in lower depths.

4.3.5.2. Eucalypts

Exchangeable calcium contents, in plantation soils, were lower than that of natural forest. The values decreased with depth in natural forest whereas in plantations of eucalypts, a steady decline with depth was not observed. The exchangeable calcium in natural forest varied from 500 to 2260 ppm while in plantations of eucalypts, the values varied from 220 to 960ppm.

In the 0-60cm depth, plantation soils had lost more than 50 per cent of exchangeable calcium. More over, the net loss from soil was found to increase with rotation. The mean values in this depth varied from 548 to 460ppm and the relative mean values for second rotation, third rotation and third rotation replanted plantations were 45, 39 and 38 per cent, respectively. The difference was significant in all the three plantations.

Nearly 60 per cent of exchangeable calcium has been lost from plantation soils in the 0-20cm and 20-40cm depths. The soils in the eucalypt plantations and natural forest

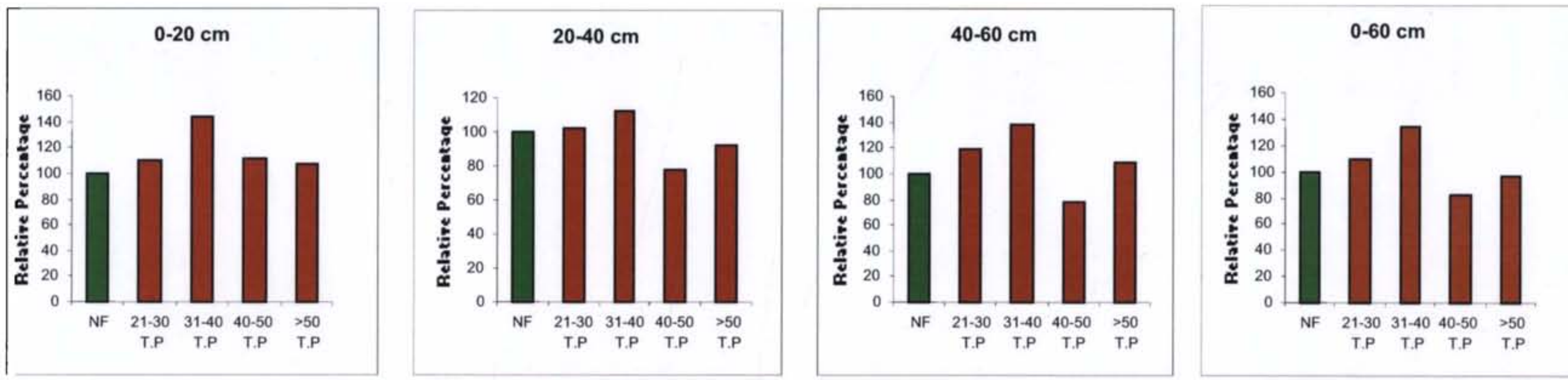

Fig.20 Relative mean values of exchangeable calcium at different depths in natural forest and teak plantations.

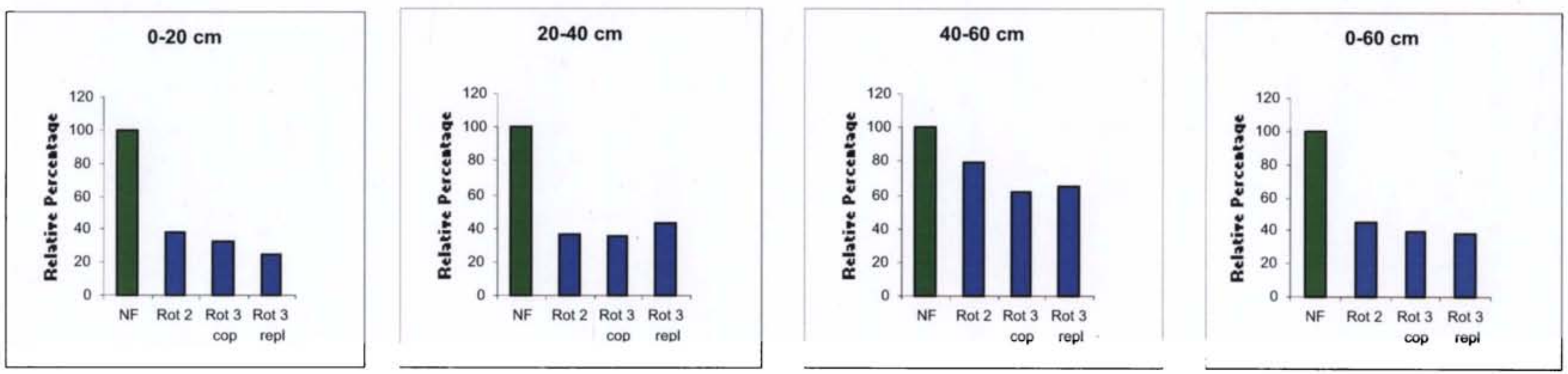

Fig.21 Relative mean values of exchangeable calcium at different depths in natural forest and eucalypt plantations.

differed significantly from each other. The mean values in the surface layer ranged from 460 to 704ppm and in the succeeding depths, the values varied from 392 to 484ppm. Calcium content in plantation soils decreased with rotation. The relative mean values in second rotation, third rotation coppiced and third rotation replanted plantations of eucalypts were 38, 33 and 25 per cent, respectively in 0-20cm depth and 36, 35 and 43 per cent, respectively in the 20-40cm depth. As in the preceding depths, in plantation soils, the values were lower than those in the natural forest in the 40-60cm depth and the decrease continued with succeeding rotation. In the 40-60cm depth, the mean values varied from 416 to 536ppm and the relative mean values for second rotation, third rotation and third rotation replanted plantations were 80, 62 and 65 per cent, respectively

4.3.5.3. Comparative evaluation

Monoculture plantations of teak and eucalypts differed in their effect on soil exchangeable calcium. Soils in younger teak plantations were richer in exchangeable calcium than natural forest. In older teak plantations, higher calcium in soils of teak than natural forest was observed in the 0-20cm depth. In the succeeding depths, the values were lower. In plantations of eucalypts, considerable loss of calcium from soils was recorded. Nearly 60 per cent of calcium was lost from soils in the 0-20cm depth. When soils in the depth of 0-60cm were considered, a loss of almost 50 per cent was recorded. Comparison of a 44-54Y old teak to an adjacent 18-20Y old eucalypt led Singh *et al.* (1990) to conclude that exchangeable calcium was higher under teak than eucalypt. No comparison with natural forest was made in the study, hence information about the net loss or gain of calcium is not available.

On comparing soils under teak and eucalypts for similar period, it was observed that the loss of calcium from eucalypts plantations was much larger than from teak. When soils in the 0-60cm depth, for 20-30years, were compared, it was observed that soils under teak recorded a 10 per cent increase while those under eucalypts lost 55 per cent of exchangeable calcium. A 10 per cent rise in soil exchangeable calcium was noticed in the 0-20cm depth of teak whereas in the corresponding depth of eucalypt plantation, a loss of 62 per cent was recorded. On comparing soils in the 0-60cm depth under plantations of teak and eucalypts for 30-40 year, a 35 per cent increase in exchangeable calcium was noticed in teak while in eucalypts a decrease of 55 per cent was observed. During the same period, in the 0-20cm depth, soils of teak gained 45 per cent calcium whereas eucalypts lost 67 per cent.

4.3.6. Exchangeable Magnesium

4.3.6.1. Teak

Exchangeable magnesium contents in the natural forest varied from 20 to 220ppm and in teak plantations, the variations was from 24 to 190ppm. In the natural forest and plantations of teak, 0-20cm depth is richest in exchangeable magnesium. However, in the youngest age class plantations *viz.*, 21-30Y, exchangeable magnesium in 0-20 and 20-40cm depths were nearly equal.

In the 0-20cm depth, the mean values varied from 99 to 134ppm. The relative mean values in 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 89, 85, 84 and 88 per cent, respectively. Exchangeable magnesium in plantation soils was lower than those of natural forest though the difference was not significant.

The mean values of exchangeable magnesium in the 20-40 and 40-60cm depths of teak soils varied from 89 to 113 and 62 to 114ppm. The relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 241, 201, 71 and 84 per cent and 125, 122, 45 and 83 per cent, respectively. In the younger age class plantations *viz.*, 21-30Y and 31-40Y, exchangeable magnesium in 20-40 and 40-60cm depths were greater than those in the natural forest. The difference was significant in the 20-40cm depth in both plantations.

In the 0-60cm depth, the mean values of exchangeable magnesium varied from 88 to 120ppm. The relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 129, 118, 64 and 85 per cent, respectively. The difference from natural forest values was significant only in 41-50Y age class plantations. Balagopalan (1995a) also observed that soils of 21-30Y age class plantation and adjacent natural forest showed no significant difference regarding exchangeable magnesium values. Similar findings were reported by Okoro *et al.* (1999). Conversely, Aborisade and Aweto (1990) Salifu and Meyer (1998) and Amponsah and Meyer (2000) found significantly lower values of exchangeable magnesium in a teak plantation when compared to an adjacent natural forest.

In all teak plantations, Ca: Mg ratio was higher in soils of 0-20cm depth than in 20-40cm depth. Calcium accumulates in greater quantities in the foliage than other cations and also does not go out of foliage just before leaf fall as a large number of other cations do. As a result, more of calcium, as compared to magnesium, is recycled from the lower depths to surface soil which affects the Calcium to Magnesium ratio. Higher Ca: Mg ratio in the upper depths relative to lower ones elucidates the active role of vegetation in pedogenesis (Bhoumik and Totey, 1990).

4.3.6.2. Eucalypts

Exchangeable magnesium in natural forest varied from 264 to 564ppm whereas in plantations, the values varied from 48 to 852ppm. In natural forest, highest value was seen in the 0-20cm depth. In the 0-20cm depth, mean values varied from 151 to 587ppm and the relative mean values for second rotation, third rotation and third rotation replanted plantations were 111, 63 and 29 per cent, respectively. Soils in second rotation eucalypt and natural forest did not differ significantly from each other in the 0-20cm depth. On the other hand, a significant decrease in exchangeable magnesium was recorded in third rotation plantations of eucalypt. Among third rotation plantations, coppiced plantations had significantly higher exchangeable magnesium than replanted ones.

In the 20-40 and 40-60cm soil depths, the mean values varied from 130 to 492 and 156 to 655ppm, respectively. The relative mean values in these depths in second rotation, third rotation and third rotation replanted plantations were 135, 80 and 36 per cent and 171, 79 and 41 per cent respectively. Exchangeable magnesium in soils of second rotation plantations of eucalypt was significantly higher than natural forest in the 20-40 and 40-60cm depths. In third rotation plantations, both coppiced and replanted, exchangeable magnesium was significantly lower than natural forest. Among plantations of eucalypt,

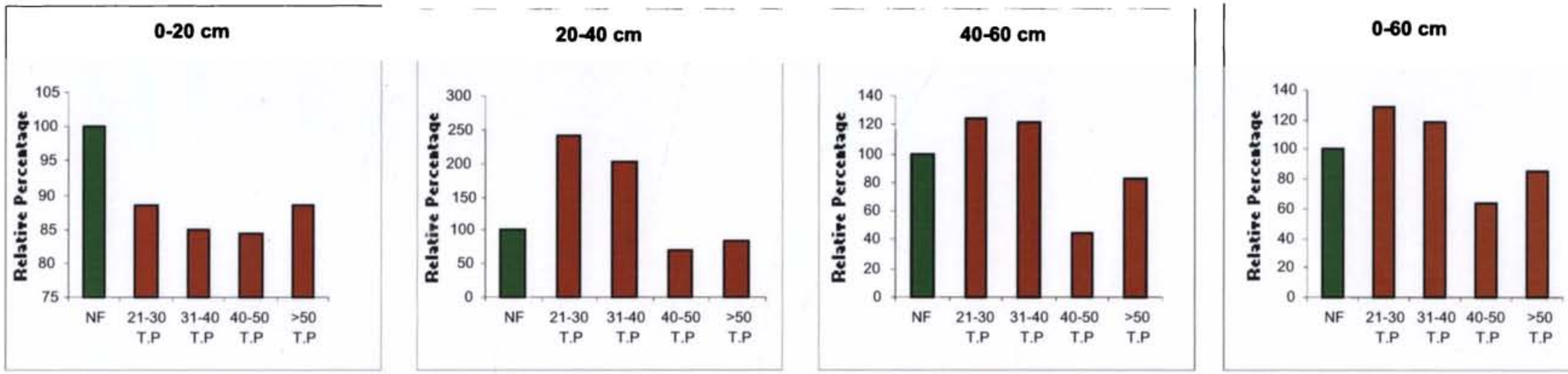

Fig.22 Relative mean values of exchangeable magnesium at different depths in natural forest and teak plantations.

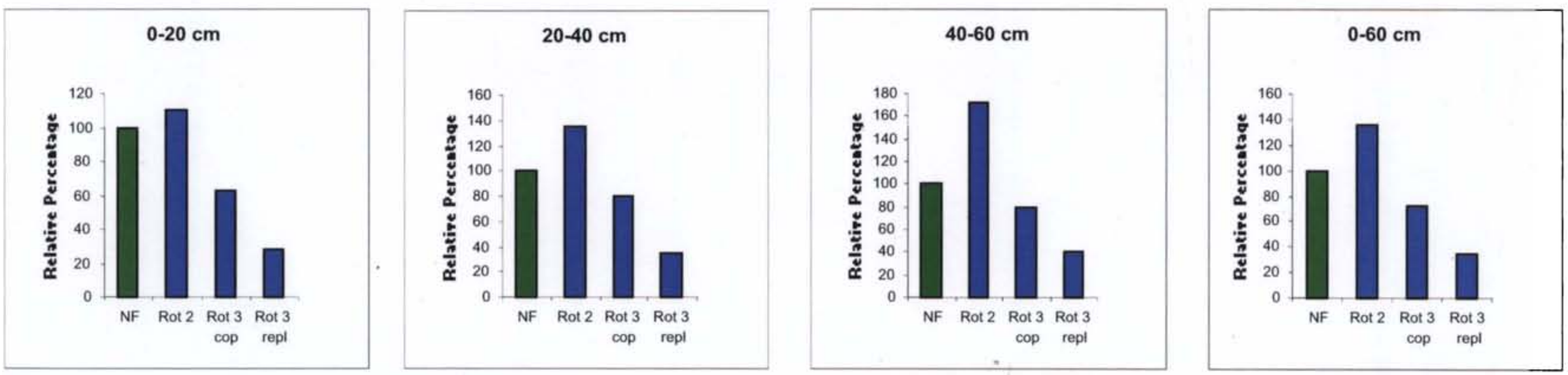

Fig.23 Relative mean values of exchangeable magnesium at different depths in natural forest and eucalypt plantations.

exchangeable magnesium in soils decreased with rotation and the decrease was significant in all the three depths.

In the 0-60cm depth, the mean values for eucalypt plantations varied from 146 to 578ppm and the relative mean values for second, third and third rotation replanted plantations were 136, 73 and 34 per cent, respectively. The values in plantations were significantly different from that of natural forest.

4.3.6.3. Comparative evaluation

On comparing soils under teak and eucalypt for 20-30Y, no significant difference from natural forest was observed in the 0-20cm depth. After 30-40Y, soils under teak did not differ significantly from natural forest in the 0-20cm depth. On the other hand, plantations of eucalypt lost 37 -71 per cent of soil exchangeable magnesium and the difference was significant.

In the 20-40cm depth, exchangeable magnesium in soils under 20-30 and 30-40Y old teak were significantly greater than natural forest. A significant increase in availability of magnesium was also observed in soils under eucalypt for 20-30Y. However, soils under eucalypt for 30-40Y had significantly lower exchangeable magnesium compared to forest soils. Soil under teak for 20-30 and 30-40Y did not differ significantly from natural forest in the 40-60cm depth. In soils under eucalypt for 20-30Y, a significant increase in exchangeable magnesium was observed in the 40-60cm depth. At the same depth, in soils under eucalypt for 30-40Y, significant decline in soil exchangeable magnesium was noticed.

4.3.7. Available phosphorus

4.3.7.1. Teak

Available phosphorus varied from 0.1 to 3.1ppm in natural forest and from 0.1 to 4.4 ppm in plantations of teak. The status of available phosphorus in soils of both natural forest and plantations were low. In both natural forest and plantations of teak, highest value for available phosphorus was recorded in the 0-20cm depth.

In 0-20cm depth, the mean values in plantations of teak varied from 0.8 to 2.7ppm while in 20-40 and 40-60cm depths, the mean values varied between 0.5 to 1 and 0.2 to 0.7 ppm, respectively. No definite pattern of variation with age of plantation was evident in teak. In the 0-20cm depth, 31-40Y age class plantation recorded marginal though significant increase over natural forest values. In older teak plantations, a significant decline with age was observed in 20-40 and 40-60cm soil depths. Balagopalan (1995b) also observed slightly lower available phosphorus values in a teak plantation compared to natural forest values in the 0-20cm depth.

In the 0-60cm depth, all the teak plantations except 31-40Y age class plantations had lower amount of available phosphorus. The difference was significant in older teak plantations. The mean values in the teak plantations varied from 0.5 to 1.2ppm. Balagopalan (1995a) observed slightly higher exchangeable phosphorus values in a teak plantation compared to natural forest values though the difference was not significant. A significant increase in available phosphorus values was observed in teak plantations by Chavan *et al.* (1995). On the other hand, Aborisade and Aweto (1990) observed that the concentrations of available phosphorus were similar in plantations of teak and natural forest, while Mongia and Bandyopadhyay (1992a) and Okoro *et al.* (2000) reported lower phosphorus values in teak soils compared to natural forest.

4.3.7.2. Eucalypts

Available phosphorus contents in natural forest varied from 0.1 to 7.4ppm and in plantations of eucalypt, the variation was from 1.8 to 20.9ppm. In the natural forest and plantation soils, highest value for available phosphorus was recorded in the 0-20cm depth. However, in third rotation replanted plantations, highest value for available phosphorus was recorded in 40-60 cm depth.

Higher availability of phosphorus in plantations of eucalypt was noticed in all the three depths and the difference was significant in the 20-40 and 40-60cm depths. It was also observed that available phosphorus in plantation soils increased with rotation though the increase was not significant. Among third rotation plantations, higher value for available

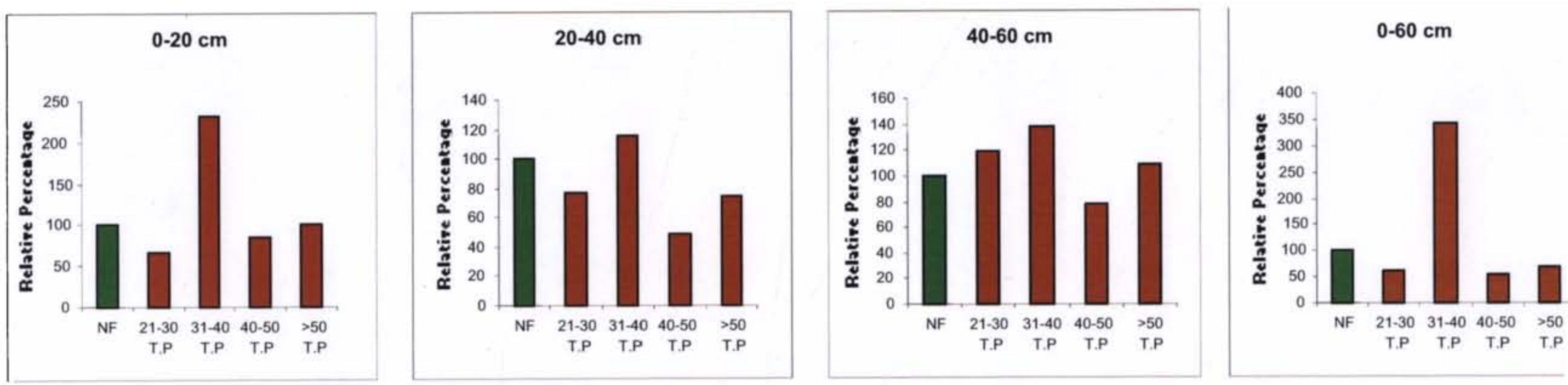

Fig.24 Relative mean values of available phosphorus at different depths in natural forest and teak plantations.

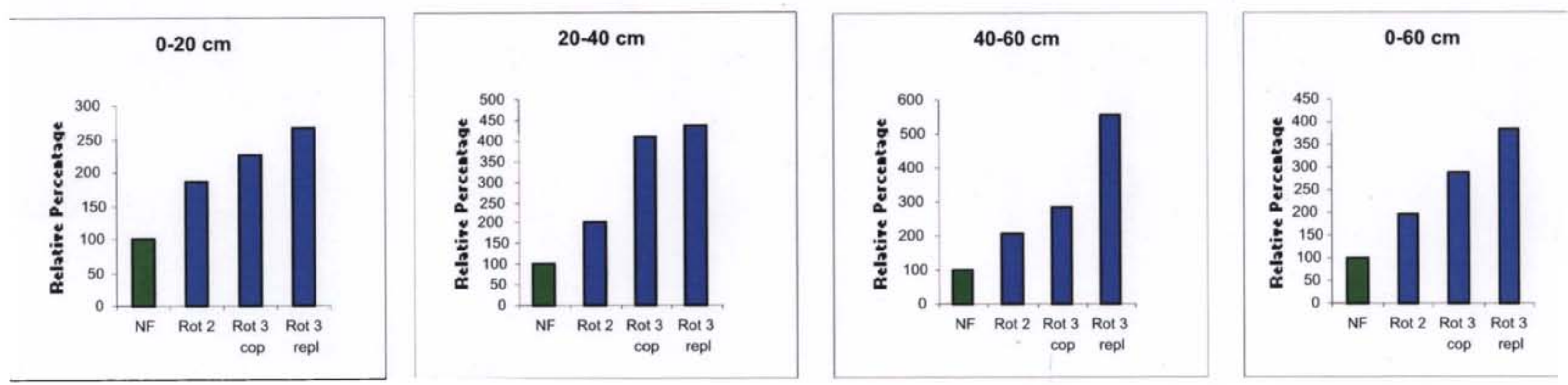

Fig.25 Relative mean values of available phosphorus at different depths in natural forest and eucalypt plantations

phosphorus was observed in replanted plantations than in coppiced ones. The same pattern of variation of available phosphorus with rotation was observed in all depths. A significant difference between replanted and coppiced plantations was observed in the 40-60cm depth. This could be due to the result of fertilizer application in the first three years after plantation establishment and its consequent leaching to lower depths.

On comparing the soils in the 0-60cm depth in natural forest and plantations, it was observed that soils in eucalypt plantations were richer in available phosphorus than natural forest. The increase was significant in third rotation plantation. This could be due to microbial link with its contents and species requirements (Jha *et al.* 1996). An increase in available phosphorus, when soils under eucalypts were compared with adjacent natural forest was also reported by Jha *et al.* (1996) and Pande (2004). On the other hand Balagopalan and Jose (1995) observed no significant difference in available phosphorus values between soils of natural forest and adjacent eucalypt plantation.

4.3.7.3 Comparative evaluation

Soils of natural forest and plantations were low in phosphorus. Significant lowering in the availability of phosphorus was observed in the 20-40, 40-60 and 0-60cm depths in older teak plantations. On the other hand, soils in eucalypt plantations demonstrated an increase in phosphorus availability with rotation. Higher available phosphorus in eucalypts plantations than teak was also reported by Chavan *et al.* (1995).

4.3.8. Organic carbon

4.3.8.1. Teak

Soil organic matter is considered the single most important indicator of soil quality and a major component in the assessment of soil quality (Sikora *et al.*, 1996). Organic carbon in natural forest varied from 1.02 to 3.09 per cent and in plantations of teak, it varied from 0.51 to 2.35 per cent. In both natural forest and plantations of teak, organic carbon decreased with depth. The sharp decrease from surface to subsurface is due to the accumulation of organic matter through leaf litter in the upper layer.

A significant lowering of soil organic carbon in the 0-20cm depth was observed in all the plantations of teak as compared to natural forest. It was also observed that organic carbon in soils first decreased and then increased with age of the plantation. Mean values of organic carbon in plantations of teak varied from 1.4 to 2.3 per cent and the relative mean values for 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 58, 53, 82 and 82 per cent, respectively. Lower organic carbon content in plantation soils compared to that of natural forest was also observed by Balagopalan (1995b, 1995a).

Younger plantations of teak had significantly lower soil organic carbon than natural forest in the 20-40 and 40-60cm depths. In contrast, soils of older teak plantations and natural forest, in these depths, did not differ significantly from each other. Mean values of soil organic carbon varied from 0.8 to 1.6 per cent in the 20-40cm depth and from 0.7 to 1.2 per cent in the 40-60cm depth. The relative mean values of organic carbon in 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations in the 20-40cm depth were 62, 46, 88 and 94 per cent, respectively. In the 40-60cm depth, the corresponding values were 66, 45, 93 and 97 per cent.

When soils in the 20-40 and 40-60cm depths in plantations of teak were studied, it was noticed that organic carbon content initially decreased and then increased with age. In all the three depths, the lowest relative mean value for organic carbon was observed in 31-40Y age class plantation. In the 0-20cm depth, the organic carbon content in older plantations was 15 to 18 per cent lower than that of natural forest. The relative mean values of organic carbon in older plantations were nearly equal to that of natural forest in the lower depths.

In the 0-60cm depth, organic carbon in teak plantations varied from 0.9 to 1.7 per cent. In all the plantations in this depth, organic carbon was significantly lower than that of natural forest. Similar findings were also reported by Salifu and Meyer (1998), Amponsah and Meyer (2000). Conversely, no significant difference between organic carbon values of a teak plantations and natural forest in Nigeria was reported by Okoro *et al.* (1999). The relative mean values of soil organic carbon in 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 61, 49, 98 and 98 per cent, respectively. Soil organic carbon in plantations of teak was found to initially decrease and then increase with age. In contrast, Suwannaratna (1999) observed that organic carbon in a fifty year old teak plantation was lower than that of a 32Y old plantation in Ghana.

The occurrence of more organic matter content in natural forest could be attributed to a number of factors including diversity of vegetation cover (Lundgren, 1978). In natural forest, greater diversity of species results in diversity of litter substrate and faster mineralization leading to enhanced organic carbon content compared to teak. Moreover lower erosion in natural forest results in greater conversion of organic matter (Maro *et al.*, 1993). For the establishment of teak plantations, the natural forest was clearfelled and slash burned. In the beginning, the soil is exposed to the environment and erosion is wide spread. This results in loss of top soil along with the organic carbon in it. However, as the plantations mature addition of litter to soil and its decomposition increases soil organic matter. Also, as teak grows, it provides a measure of cover to the soil. However, plantations of teak are subjected to mechanical and silvicultural thinning. The disturbance to the soil during the above processes and decrease of soil cover leads to loss of soil organic carbon. Litter production at this stage appears to be inadequate to balance for the loss of organic carbon. The net result is progressive loss of soil organic carbon. The mechanical and silvicultural thinnings end by 25 years. Now soil starts to recuperate. It is probable that at this stage, the rate of nutrient return to the soil through the fall and break down of litter is greater than its loss from soil. Thus an increase in soil organic carbon occurs. In the older age class plantations, the values approach those of natural forest.

4.3.8.2. Eucalypts

Organic carbon in natural forest varied from 0.85 to 4.73 per cent and in plantations of eucalypts, it varied from 0.51 to 3.0 per cent. In both natural forest and plantations of eucalypt, organic carbon decreased with depth. The sharp decrease from surface to subsurface is due to the accumulation of organic matter through leaf litter in the upper horizons. Soil organic carbon in all plantations of eucalypts were lower than that of natural forest The higher organic matter content in natural forest relative to plantations may be because of diversity of vegetation cover (Lundgren, 1978), litter, its faster

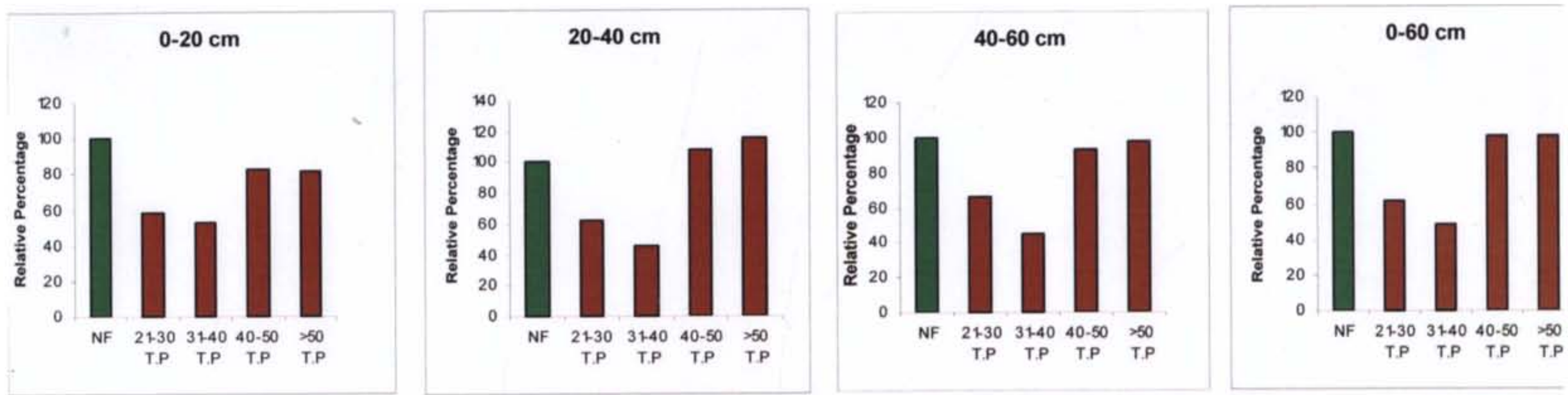

Fig.26 Relative mean values of organic carbon at different depths in natural forest and teak plantations.

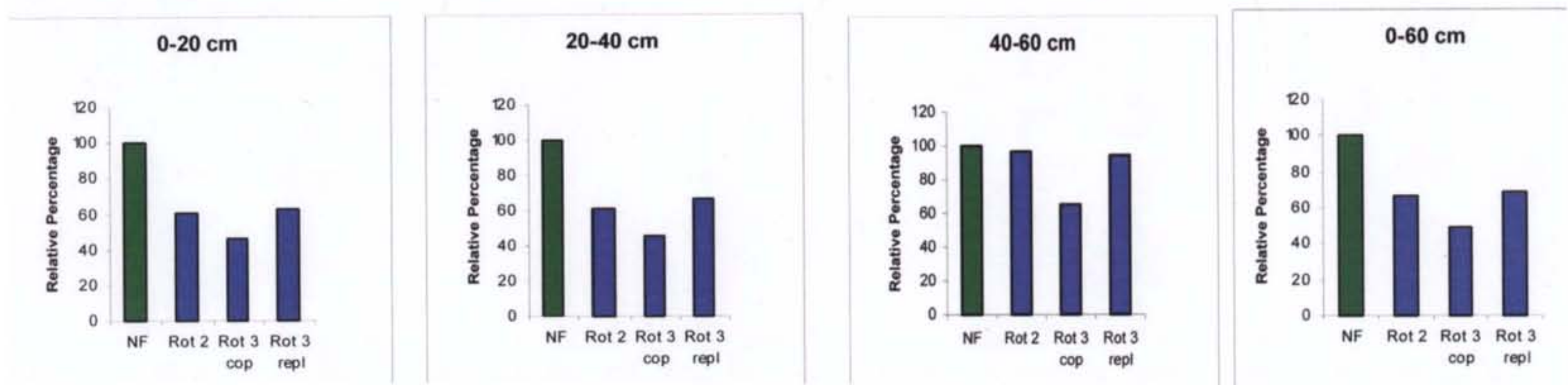

Fig.27 Relative mean values of organic carbon at different depths in natural forest and eucalypt plantations.

mineralization and lower erosion (Maro *et al.*, 1993). The disturbance to soil during clearfelling, and the loss of soil cover in the initial years of plantation establishment often leads to enhanced erosion and loss of top soil rich in organic matter. Moreover, shorter rotation is thought to result in long-term decline in soil carbon content, as there is more frequent cultivation and disruption to the flow of carbon to the soil through litter (Polglase *et al.*, 2000). The organic carbon status of plantations and natural forest differed most in the surface.

In the 0-60 cm depth, the mean values for organic carbon varied from 1.41 to 1.97 per cent. The relative mean values of organic carbon in soils of second and third rotation and third rotation replanted plantations were 67, 49 and 69 per cent, respectively. The difference was significant. Mean values of soil organic carbon in the 0-20, 20-40 and 40-60cm depths in the eucalypt plantations, varied from 1.97 to 2.58, 1.32 to 1.91 and 0.93 to 1.37 per cent, respectively. The relative mean values in second and third rotation and third rotation replanted plantations were 61, 46 and 63; 61, 46 and 67 and 97, 65 and 94 per cent, respectively. A significant decline in soil organic carbon compared to natural forest was observed in the 0-20 and 20-40cm depths. In the 40-60cm depth, organic carbon contents in the natural forest and plantations of eucalypt did not differ significantly from each other. Decline in organic carbon content in eucalypt plantation was reported by Balagopalan and Jose (1986, 1995), Balagopalan (1995b), Sunita and Uma (1993), Bargali *et al.* (1993) and Michelsen *et al.* (1996) and Geetha and Balagopalan (2005b).

Organic carbon in plantations of eucalypts were found to decrease with rotation. A decrease in organic carbon with rotation was previously described by Balagopalan and Jose (1983) and Balagopalan (1995b). Replanted plantations of eucalypt were richer in organic carbon than the corresponding coppiced one. This pattern of variation was noticed in all the three depths. Replanted plantations were fertilized after their establishment. This fertilizer application could have increased the growth of eucalypt that would translate into higher litter fall and eventually higher organic matter in the soils under it. Reports of increase in soil organic carbon as a result of fertilizer application exists (Hussein, 1995, Johnson, 1992). On the other hand, in coppiced plantation, where fertilizer was not applied, organic carbon was lower.

4.3.8.3. Comparative evaluation

Soils in teak and eucalypt plantations were poorer in organic carbon than those in the natural forest and the difference between plantations and natural forest was most pronounced in the upper layer. The decrease in soil organic matter in the plantations may be explained by the low rate of addition and incorporation of fresh and partially decomposed litter material, while the normal rate of oxidation of soil organic matter continues (Balagopalan, 1995b). In teak plantations, soil organic carbon was found to initially decrease and then increase with age, with the soils of oldest plantation approaching natural forest in organic matter content. In eucalypt plantations, no such pattern of variation was observed. Amount of organic carbon in soils decreased with rotation, although in replanted plantations, an increase in organic carbon content was observed. When plantations under teak and eucalypts for similar period of time were compared, it was observed that in the 0-20cm depth, teak lost 42 per cent of organic carbon while eucalypt lost 39 per cent in 20-30Y period. On the contrary, after 30-40Y period, the loss from 0-20cm depth of teak was 48 per cent and in eucalypts it was 54 per cent. The loss for replanted eucalypts during the same period was only 38 per cent. Soils under teak for more than 40 years show a dramatic increase in organic carbon content. From the data available, such an increase in eucalypts cannot be expected. Greater decline in organic carbon content of eucalypt plantations than that of teak was also reported by Geetha and Balagopalan (2005b) and Balagopalan and Geetha (2006). Conversely, Singh *et al.* (1990) observed that organic carbon in a 18-20Y old eucalypt plantation was higher than that of a 44-54Y old teak plantation.

4.3.9. Total Nitrogen

4.3.10.1. Teak

Total nitrogen contents in natural forest varied from 0.095 to 0.39 per cent and in plantations of teak, the variation was from 0.09 to 0.40 per cent. Total nitrogen in soils was highest in the surface and decreased with depth in natural forest and teak plantations. However, this pattern was not fully observed in 21-30Y age class plantations. In this age class, although the highest value for total nitrogen was reported in the upper layer, a decrease in the amount of total nitrogen with depth was not seen.

No significant difference was observed in the amount of total nitrogen in soils of teak plantations and natural forest. In the 0-20cm soil depth, total nitrogen in soils varied from 0.28 to 0.35 per cent. The relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 96, 97, 103 and 103 per cent, respectively. Total nitrogen in soil increased with the age of the plantations. Mean values of total nitrogen varied from 0.16 to 0.26 per cent and from 0.18 to 0.19 per cent in the 20-40 and 40-60cm depths, respectively. The relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 68, 93, 98 and 115 per cent and 116, 109, 120 and 137 per cent, respectively.

When the soil up to a depth of 60cm was considered, it was observed that, total nitrogen in younger plantations were lower than that of natural forest though in older plantations the values were higher. The difference was not significant. Lower total nitrogen in a plantation of teak compared to adjacent natural forest was reported by Aborisade and Aweto (1990), Mongia and Bandyopadhyay (1994), Salifu and Meyer (1998), Amponsah and Meyer (2000). The mean values for total nitrogen in this depth varied from 0.21 to 0.27 per cent. The relative mean values of 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 91, 99, 105 and 114 per cent, respectively. Chamshama *et al.* (2000) observed that total nitrogen decreased in young Ist rotation teak plantations and increased in semi mature teak plantations of Tanzania. This corroborates the findings of the present study.

In teak plantations, total nitrogen was observed to increase with age though the difference was not significant. This trend is clearly visible in the two upper layers. Due to the plantation activities in the initial year of its establishment, loss of top soil with its accompanying loss of nitrogen leaves behind a soil that is low in nitrogen content. As the plantation ages, addition of litter, its mineralization and incorporation into the soil enhances the nitrogen content of soil. Total nitrogen is significantly and positively correlated to organic carbon and mirrors the variation of organic carbon in soil.

4.3.9.2. Eucalypts

Total nitrogen in soils of natural forest varied from 0.16 to 0.38 per cent while in plantations of eucalypts, the range was between 0.05 to 0.28 per cent. Total soil nitrogen decreased with depth in natural forest though this pattern was not distinctly discernible in plantations.

The mean values for total nitrogen in plantations of eucalypt varied from 0.13 to 0.24 per cent in 0-20cm and from 0.09 to 0.14 per cent in 20-40cm depths. The relative mean values in the 0-20cm and 20-40cm depths in the plantations were 71, 38 and 58 per cent and 48, 33 and 43 per cent, respectively. The decrease was significant in the 0-20 and 20-40cm depths. Similar findings were earlier reported by Balagopalan and Jose (1986). Among third rotation plantations, higher value for total nitrogen was observed in the replanted plantations compared to coppiced ones. The main source of nitrogen in soil is organic matter. The loss of soil organic matter during clear felling and plantation establishment translates into lower total nitrogen in soils of eucalypt plantations. In short rotation crop like eucalypt, where disruption of carbon cycle is more frequent, each rotation is accompanied by decrease in soil organic matter and consequent lowering of total nitrogen.

Among third rotation plantations, higher total nitrogen was observed in soils of replanted plantations than coppiced ones. Replanted plantations were fertilized in their initial years. These additional nutrients would have enhanced growth and increased nutrient return to soil through litter fall. This in turn would have led to improved organic matter status enriching the total nitrogen in soil. Fertilizer application also adds nitrogen to the soil directly thereby increasing total nitrogen content.

In the 40-60cm depth, mean value of total nitrogen varied from 0.096 to 0.15 per cent and the relative mean values of second and third rotation and third rotation replanted plantations were 79, 70 and 50 per cent, respectively. In this depth too total nitrogen

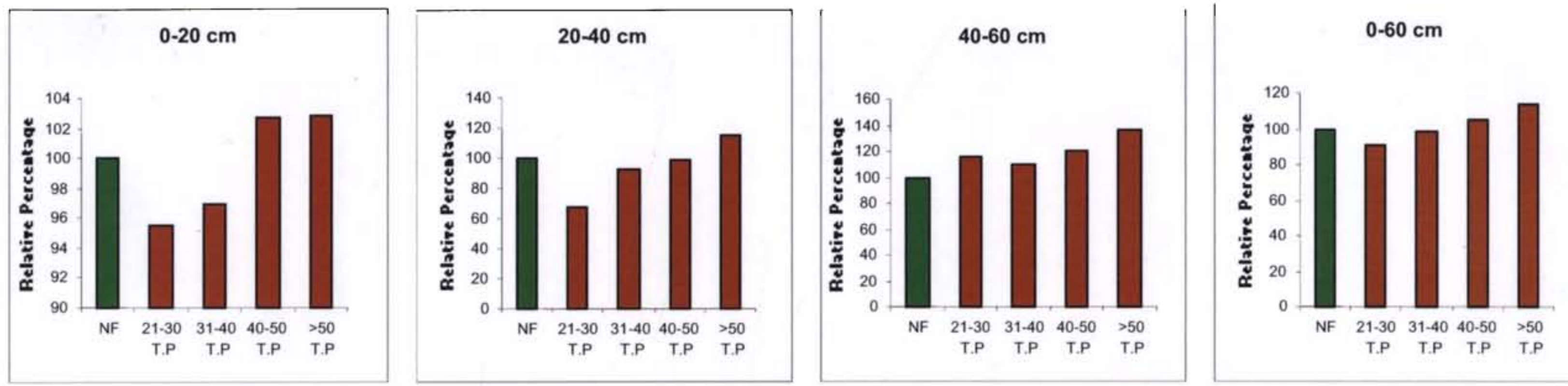

Fig.28 Relative mean values of total nitrogen at different depths in natural forest and teak plantations.

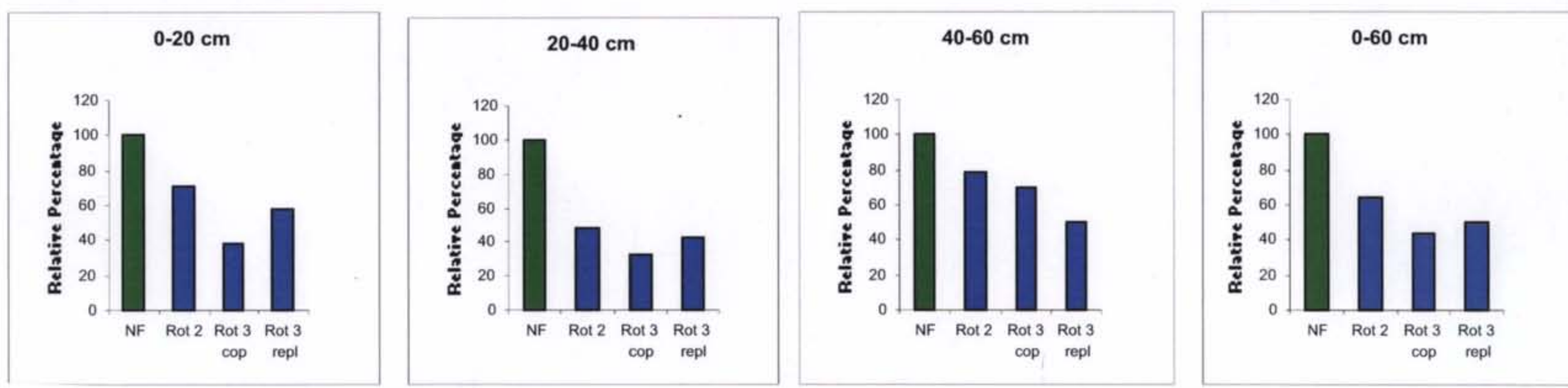

Fig.29 Relative mean values of total nitrogen at different depths in natural forest and eucalypt plantations

decreased with rotation, though replanted plantations had lower soil nitrogen than coppiced plantations.

In the 0-60cm depth, total nitrogen was significantly lower than that of natural forest and decreased with rotation. The mean values for total nitrogen in plantations of eucalypt varied from 0.12 to 0.17 per cent. The relative mean values in the 0-60cm depth for second, third and third rotation replanted plantations were 65, 44 and 51 per cent, respectively. A decrease in total nitrogen with rotation in uncoppiced, first and second coppiced eucalypt was reported by Balagopalan and Jose (1983) and Balagopalan (1995b). A decrease in total soil nitrogen as a result of reforestation with eucalypts was also reported by Bargali *et al.* (1993) Sunita and Uma (1993) and Balagopalan and Jose (1995).

4.3.9.3 Comparative evaluation

The amount of nitrogen in soil organic matter is much greater than in the biomass. So loss of nitrogen depend more on the amount of soil nitrogen mineralized than nitrogen removed in logging (Smethurst and Nambiar, 1990) or held up in biomass. Total nitrogen in soils of teak plantations and natural forest did not differ significantly from each other. On the other hand, in plantations of eucalypt, a significant decline was observed in 0-20 and 20-40cm depths. When soils in teak and eucalypts for similar periods of time were considered, it was observed that after 21-30 years, plantations of teak lost 9 per cent total nitrogen while those under eucalypt lost 35 per cent from 0-60cm soil depth. In the 0-20cm soil depth, plantations of teak lost 4 per cent, while those of eucalypt lost 29 per cent of total nitrogen. The loss from 20-40cm soil depth in plantations of teak was 32 per cent while in plantations of eucalypt, it was 52 per cent. The soils of 40-60cm depth in plantations of eucalypts was poorer by 82 per cent.

On comparing soils under teak and eucalypts for 31-40Y, it was observed that plantations of teak and the adjacent natural forest had similar amounts of total nitrogen. On the other hand, soils under eucalypts had suffered a loss of 50-57 per cent. The loss from 0-20cm depth in plantations of teak was 3 per cent while in eucalypt, it was 62 per cent. In the 20-40cm depth, teak plantations lost 7 per cent and eucalypt lost 58-68 per cent of total soil nitrogen. Soils under teak in the 40-60cm depth were richer in organic carbon than natural forest while those under eucalypts were poorer than natural forest by 30-40 per cent. Greater loss of total soil nitrogen from plantations of eucalypt than teak was earlier reported by Balagopalan and Jose (1993, 1997) and Balagopalan (1995b). Conversely, Singh *et al.* (1990) noted that total nitrogen was higher in 18-20Y old eucalypt than 44-50Y old teak.

4.3.10 Carbon : Nitrogen Ratio

4.3.10.1 Teak

The carbon to nitrogen ratio, an index of fertility was calculated. The carbon to nitrogen ratio in soils of natural forest and that of older teak plantations were close.

The mean C:N ratio, in the 0-20cm, 20-40cm and 40-60cm depths in the 21-30Y, 31-40Y, 41-50Y and>50Y age class plantations varied from 5.0 to 6.9, 4.1 to 7.4 and 4.3 to 7.2, respectively. The relative mean values of these plantations in the 0-20cm depth were 67, 56, 83 and 82 per cent and in the 20-40cm, it was 80, 44, 89 and 80 per cent, respectively. The relative mean values in the 40-60cm depth were 61, 47, 81 and 70 per cent, respectively.

In the 0-60cm soil depth, C:N ratio in plantations of teak varied from 4.5 to 7.7 and the relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 69, 49, 99 and 79 per cent, respectively. The C:N ratio in younger teak plantations were lower than that of older plantations and the lowest value was observed in 31-40Y age class plantations. The same pattern of variation was also observed in all the depths under study. The C:N ratio of younger teak plantations and natural forest differed significantly from each other. In older teak plantations, the difference was significant in the 20-40 and 40-60cm depths.

4.3.10.2. Eucalypts

The C:N ratio in plantations of eucalypt were higher than that of natural forest. The wide C:N ratio of the soils is an indication of decline in soil fertility (Lal, 1973). Both carbon

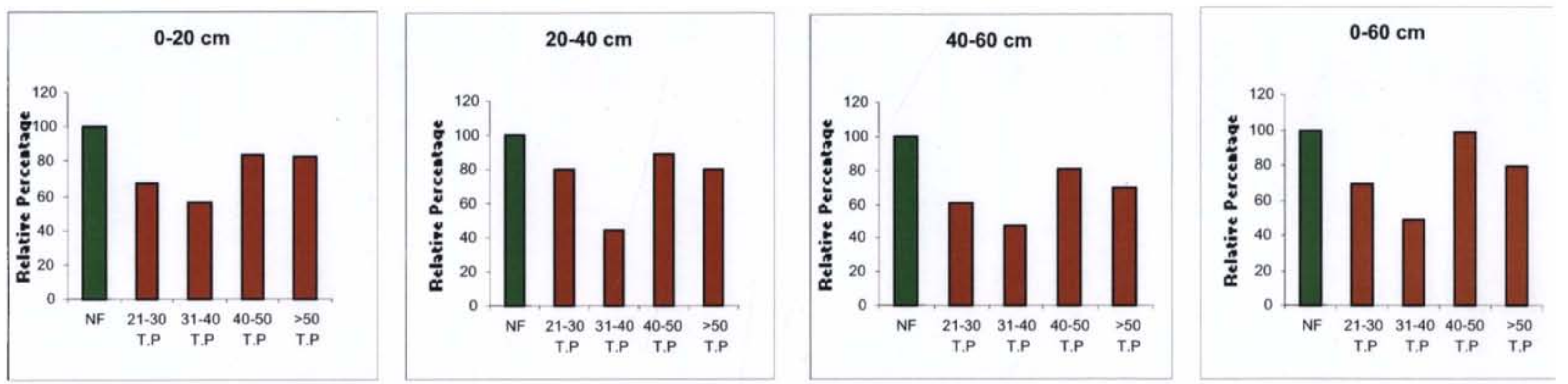

Fig.30 Relative mean values of carbon to nitrogen ratio at different depths in natural forest and teak plantations.

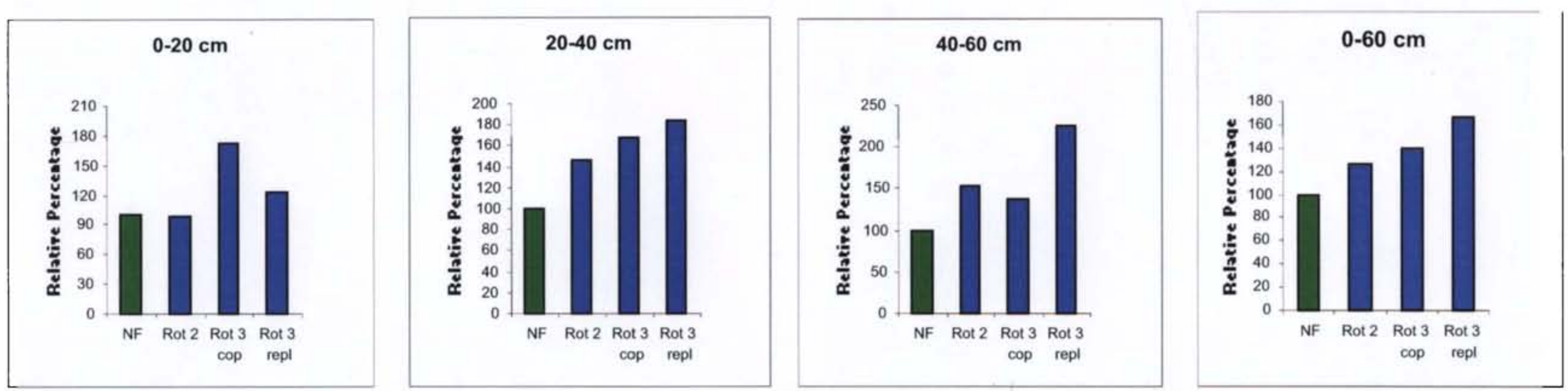

Fig.31 Relative mean values of carbon to nitrogen ratio at different depths in natural forest and eucalypt plantations

and nitrogen in eucalypt plantations were lower than that of natural forest, but the decrease in the amount of nitrogen was greater than the decrease of organic carbon. This is responsible for the higher C:N ratio in plantations of eucalypt. In the 0- 60cm depth, the C:N ratio in plantations of eucalypt varied from 11 to 14.5 and the relative mean values for second, third and third rotation replanted plantations were 127, 140 and 168 per cent, respectively. C:N value varied significantly between natural forest and plantations. The mean C:N ratio in the 0-20cm and 20-40cm depths in these plantations varied from 11.1 to 14.0 and from 12.5 to15.7, respectively. The relative mean values of second, third and third rotation replanted plantations in the 20-40cm depth were 146, 167 and 183 per cent and in the 40-60cm depth the values were 152, 137 and 224 per cent, respectively.

4.3.10.3. Comparative evaluation

Plantations of teak showed lower C:N ratio than that of natural forest while the value was higher in plantations of eucalypt. C:N ratio of younger teak plantations were lower than. that of older teak plantation. In plantations of eucalypts the C:N ratio increased with rotation

4.3.11. Correlation studies

Correlation between the soil properties is given in Appendix 76. Some of the physical properties of soils *viz.*, bulk density, particle density, pore space and water holding capacity were correlated with organic carbon. Bulk density was seen to have a significant negative correlation with organic carbon. Similar findings were reported by Korschens and Greilich (1981), Hutington *et al.* (1988) and Mandal *et al.* (1990). Organic matter helps in granulation and encourages a porous condition thus lowering bulk density. Hence, lowering of organic matter in plantation soils may contribute to its increased compaction. The trend in bulk density was influenced by the variation in organic carbon status of plantation soils. Highest relative mean bulk density and lowest relative mean organic carbon values were observed in the same age class plantations *viz.*, 31-40Y.

Water holding capacity was observed to have significant and negative correlation with bulk density and significant positive correlation with organic carbon. Higher organic matter as indicated by higher organic carbon in soil enhances water holding capacity. As soils of plantations had lower organic matter than natural forest, water holding capacity was also lower. Thus, it was observed that the single most important factor that influences soil physical properties was organic carbon status of soils.

Significant correlations were observed between some of the soil chemical properties and macronutrients. Exchangeable bases showed a significant positive correlation with exchangeable sodium, potassium, calcium and magnesium. Exchangeable calcium was significantly and positively correlated with pH, exchangeable base, exchangeable magnesium and organic carbon. Exchangeable magnesium in soil was significantly and positively correlated with pH, exchangeable bases, exchangeable potassium and calcium. Total nitrogen was significantly and positively correlated to organic carbon and its status mirrors the variation of organic carbon content in soil.

Chapter 5

Micronutrient Status

5.1. Introduction

Soils vary widely in their micronutrient content and their ability to supply micronutrients in quantities sufficient for optimal crop growth. Soils deficient in their ability to supply micronutrients to crops are alarmingly widespread across the globe. Original geologic substrate and subsequent geochemical and pedogenic regimes determine total levels of micronutrients in soils. However, total levels are rarely indicative of plant availability, because availability depends on soil texture, pH, organic matter content, adsorptive surfaces, and other physical, chemical, and biological conditions in the soil (White and Zasoski, 1999; Malewar, 2005).

A major portion of micronutrients is fixed by organic and inorganic colloids of the soil. As a result, the total amounts of micronutrients in the soils may not be exchangeable to plants (White and Zasoski, 1999). Essentially, every aspect of chemistry in micro-nutrients in soils is related to reactions that involve organic substances. Hence any change in the organic matter content of soil may be accompanied by concomitant changes in cycling of micronutrients (Stevenson, 1991). Moisture, aeration, clay, pH and nutrients in the soils also affected micronutrient availability. Various researchers have investigated the relationship of exchangeable iron, copper, zinc and manganese to pH, organic matter, clay and cation exchange capacity (Rajagopal *et al.*, 1974, Sakal *et al.*, 1988).

Each nutrient has a specific role to perform in influencing plant growth, development, yield and quality of crop. The micronutrient cations are involved in enzyme systems as co-factors. With the exception of Zn, these are capable of acting as electron carriers in the enzyme systems which are responsible for the oxidation – reduction reaction in plants. They also play a major role in building up chloroplasts and help in photosynthetic activities (Deb and Sakal, 2002; Havlin *et al.*, 2003). Awareness about importance of micronutrients is now wide spread. As per the All India Coordinated Research Project for Micronutrients, 48 per cent samples at all India level were deficient in zinc, 12 per cent in iron and 5 per cent in manganese. The deficiency of Mo is not widely seen in Indian (Singh *et al.*,1979) though, a few instance of deficiency has been reported from Vijaynagaram, A.P. (Singh, 2004)

In India, boron deficiency has been reported from eastern parts, namely Bihar, Jharkhand, West Bengal, Assam and Orissa (Deb and Sakal, 2002) The range of total and exchangeable micronutrient contents in Indian soils are given in Table 6.

Table 6. Total and exchangeable micronutrient contents in Indian soils

Micronutrient	Total content (mg/Kg soil)	Exchangeable micronutrient (mg/Kg soil)	
		Content	Mean
Zinc	1 to 1019	0.2 to 6.9	0.9
Copper	1.9 to 960	0.1 to 8.2	2.1
Iron	2700 to 191,000	0.8 to 196	19
Manganese	37 to 11,500	0.2 to 118	21

There is no universal definition for critical limits of micronutrients in soils and plants. The critical limits of different micronutrients in soils have been found to vary with the extractant used, soil to extractant ratio, equilibration period, crops and their cultivars, soil properties like texture, soil pH, calcium carbonate, organic matter, available phosphorus, level of fertility and effect of cropping sequence (Malewar, 2005). Information about micronutrient status of forest or plantation soils, especially in India, is scarce and limited in number (Nitant *et al.*, 1992, Thiyageshwari *et al.*, 2006, Rahman and Elahi, 2006, Jianwei Li *et al.*, 2006). A few studies on effect of micronutrient deficiency on growth of teak and eucalypt were limited to seedling stages at the nursery level (Sujatha, 2003; Gopikumar *et al.*, 2001; Kamala *et al.*, 1986). Sujatha (2003) observed that among Fe, Cu, Mn, Zn, Mo and B, deficiency symptom of Fe was observed earliest while that of B was noticed last in teak. It was also observed that among the micronutrients studied, deficiency of B affected the growth of teak seedlings least. In the case of eucalypt, at the end of the seedling production rotation, Silveira *et al.* (2003) observed that, Mn was the most extracted micronutrient while B was the least. This showed that the demand of B for teak and eucalypt was relatively low when compared with Fe, Cu, Mn and Zn.

Conversion of natural forest to monoculture plantations influences physical and chemical properties of soils. This can, in turn, affect the micronutrient status. Considering the relative importance of Fe, Cu, Mn and Zn to teak and eucalypt and the extent of their deficiency in India, a study on status of these micronutrients in forest and plantations soils was carried out.

5.2. Materials and Methods

Exchangeable micronutrients *viz*., iron, copper, manganese and zinc were extracted from the soil by 0.1M hydrochloric acid as an extractant in 1:10, soil: solution ratio (20g soil: 200ml solution), shaken for five minutes and filtered with Whatman no. 1 filter paper. The 0.1M hydrochloric acid extractant was prepared by adding 300mL of 6M hydrochloric acid to approximately 10L of deionized water and diluting to 18.0L final volume.

In order to prepare standard calibration curves of Zn, Cu, Mn, and Fe, six standards of each were prepared from 1000mgL^{-1} standard solutions, readily available from M/s Merck Chemicals. The concentration of solutions prepared were 0.1, 0.5, 1.0, 2.0, 4.0 and 5.0mgL^{-1} for Zn and Cu; 0.1, 1.0, 2.0, 4.0, 8.0 and 10 mgL^{-1} for Mn and Fe. For this, 10ml of 1000mgL^{-1} standard solutions of Zn were pippeted out and diluted to 100ml. This was 100mgL^{-1} standard solution. From this standard solution, 25 ml was diluted to 250ml, to obtain 10mgL^{-1} standard solution. Similar dilutions were made with 1000mgL^{-1} standard solutions of Cu, Mn, and Fe.

In the case of Zn and Cu, 10, 20, 40 and 50ml standard solutions were pippeted out and made up to 100ml in order to prepare 1.0, 2.0, 4.0 and 5.0mgL^{-1} standard solutions, respectively. To prepare 0.1 and 0.5mgL^{-1} standard solutions, 10 and 50ml of 1.0mgL^{-1} standard solutions were diluted, respectively to 100ml.

For preparing1.0, 2.0, 4.0 and 8.0mgL^{-1} standard solutions of Mn and Fe, 10, 20, 40 and 80 ml 10mgL^{-1} standard solutions were pippeted out and diluted to 100ml. The 0.1mgL^{-1}

standard solutions of Mn and Fe were prepared by diluting 10ml of 1.0mgL^{-1} respective standard solutions to 100ml.

The above standards were fed into the atomic absorption spectrophotometer (Perkin Elmer) and standard curves for each micronutrient generated (Page *et al.*, 1982). Similarly, the filtrate was fed into the atomic absorption spectrophotometer and the concentrations read. In the case of higher concentrations appropriate dilutions were made.

ANOVA was done for each location and for each depth level separately for comparing between vegetation. To study the soil changes over time, ANOVA was done for each age class and depth level. If the analysis of variance was found to be significant, Least Significant Difference was used for pair wise comparison. The analysis was carried out using SPSS software package (Norusis, 1988).

5.3. Results and Discussion

The mean values of soil micronutrients in natural forest and plantations of teak are described in Table 7 and those of natural forest and eucalypts are described in Table 8. Results of analysis of variance of soil properties due to vegetation types are given in Appendices 51 to 62. ANOVA between soils of natural forest and different age class teak plantations and those of the natural forest and different rotation eucalypt plantations are given in Appendices 63 to 75. Correlation between the soil properties are given in Appendix 76.

5.3.1. Exchangeable Iron

5.3.1.1. Teak

Exchangeable iron in soils of natural forest varied from 6.5 to 55.25ppm whereas in plantations of teak, it varied from 6.7 to 84.0ppm. Among plantations of teak, exchangeable iron first increased and then decreased with age. This pattern of variation was seen in 0-20, 20-40 and 40-60cm depths. The highest mean value for exchangeable iron was obtained in 31-40Y age class plantations in all depths.

Soils of younger teak plantations had significantly higher amount of exchangeable iron than natural forest in all the three depths. In the 0-20cm depth, availability of iron was significantly higher in 31-40Y age class plantations than in natural forest. However, in the 41-50Y and >50Y age class plantations, iron availability was significantly lower than in natural forest. The relative mean values for these plantations were 150, 261, 58 and 41 per cent, respectively. The mean values of exchangeable iron in this layer varied from 17.5 to 57.2ppm.

In the 20-40 and 40-60cm depths, the mean values varied from 20.0 to 50.4ppm and 20.2 to 51.9ppm. The relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 141, 306, 117 and 81 per cent in the 20-40cm depth while in 40-60cm depth, the values were 107, 276, 101 and 86 per cent, respectively. Soils with natural forest and teak, with the exception of 31-40Y age class plantations, did not differ significantly in iron availability in the 20-40 and 40-60cm depths. In 31-40Y age class plantations, significantly higher amount of iron was available to plants than in natural forest.

The mean values of exchangeable iron in 0-60cm depth varied from 19.7 to 53.2ppm. The relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 131, 320, 86 and 64 per cent, respectively. The difference was significant in younger teak plantations and non-significant in older teak plantations. Studies on variation in micronutrient availability with age in teak plantations or comparison with natural forest were not reported previously.

A study by Karia and Kiran (2004) on micronutrients in forest soils of Chhotaudepur exist but it does not cover the micronutrient status of teak plantations. Reported mean value of exchangeable iron in the surface soil of a closed teak forest was higher than in the present study.

Table 7. Mean values of exchangeable micronutrients in natural forest and teak plantations

Study area	Location	Vegetation	Age class	Depth --cm--	Exchangeable Micronutrients Fe	Cu	Zn	Mn
					----------	ppm	----------	
Vazhachal Forest Division	Site I Karadipara	Natural forest	-	0-20	14.53	0.49	1.44	38.77
				20-40	16.5	0.41	0.88	21.10
				40-60	18.8	0.58	0.97	22.68
				0-60	16.6	0.47	1.10	27.52
		Teak	21-30Y	0-20	21.8	1.89	1.09	78.60
				20-40	23.2	2.30	0.79	31.32
				40-60	20.2	1.98	0.72	47.66
				0-60	21.8	2.06	0.86	52.53
			31-40Y	0-20	57.2	1.64	1.36	52.94
				20-40	50.4	1.68	1.00	22.57
				40-60	52.0	1.94	1.07	22.67
				0-60	53.2	1.75	1.14	32.73
	Site II Athirapilly	Natural forest		0-20	43.0	0.65	1.74	45.09
				20-40	24.8	0.59	0.79	24.44
				40-60	25.4	0.51	0.72	17.02
				0-60	31.1	0.62	1.08	28.85
		Teak	40-50Y	0-20	24.7	1.42	1.48	31.53
				20-40	29.1	1.68	1.30	16.18
				40-60	25.9	1.28	0.87	14.34
				0-60	26.5	1.46	1.21	20.68
			>50Y	0-20	17.47	1.55	1.33	38.57
				20-40	20.0	1.79	0.84	31.63
				40-60	21.8	1.65	0.75	28.89
				0-60	19.7	1.66	0.97	33.03

Table 8. Mean values of exchangeable micronutrients in natural forest and eucalypt plantations

Study area	Location	Vegetation	Rotation	Depth --cm--	Exchangeable Micronutrients Fe	Cu	Zn	Mn
					--------------ppm--------------			
Thrissur Forest Division	Marotichal	Natural forest	-	0-20	7.64	2.19	2.17	66.58
				20-40	8.44	2.55	1.18	36.34
				40-60	11.16	3.89	1.20	33.30
				0-60	9.08	2.88	1.52	45.41
		Eucalypt	Rotation 2	0-20	9.40	2.12	3.60	42.62
				20-40	10.30	3.88	1.81	50.92
				40-60	11.56	2.37	1.76	49.40
				0-60	10.42	2.79	2.39	47.65
			Rotation 3 replanted	0-20	13.38	1.06	1.58	23.82
				20-40	11.08	0.94	0.75	17.52
				40-60	13.90	0.91	1.81	14.18
				0-60	12.79	0.97	1.38	18.51
			Rotation 3 coppiced	0-20	16.18	1.78	1.95	27.42
				20-40	25.80	1.72	0.85	20.74
				40-60	29.26	1.55	0.86	26.34
				0-60	23.75	1.68	1.22	24.83

5.3.1.2. Eucalypts

The amount of exchangeable iron in the soils of natural forest increased with depth. Similar trend was also observed in second and third rotation eucalypt plantations. However, this pattern of variation was not observed in third rotation replanted plantations, possibly due to soil disturbance during replanting. Exchangeable iron in soils of natural forest varied from 5 to 14.1ppm and in eucalypt plantations, the variation was from 4.5 to 33.9ppm.

In 0-20cm depth, the corresponding values were 123, 212 and 175 per cent, respectively. The mean values of exchangeable iron in the 0-20cm depth varied from 9.4 to 16.2ppm and increased significantly with rotation. The same pattern of change was observed in all the three depths. Among third rotation plantations, availability of iron in coppiced plantation was higher than replanted one. In the 20-40 and 40-60cm depths, the mean values varied from 10.3 to 25.8ppm and from 11.6 to 29.3ppm. The relative mean values of second, third and third rotation replanted plantations were 122, 306 and 131 per cent and 104, 262 and 125 per cent, respectively.

Soils in eucalypt plantations had significantly higher values than that of natural forest in 0-60cm depth. The mean values varied from 10.4 to 23.8ppm. The relative mean values in second, third and third rotation replanted plantations were 115, 262 and 141 per cent, respectively. The increase from natural forest was significant in third rotation plantations. On comparing the soils of coppiced and replanted third rotation plantations, it was observed that exchangeable iron in replanted plantations was lower than in coppiced one. In plantations of eucalypts, exchangeable iron increased significantly with rotation in all depths. Higher iron availability in older eucalypt plantations than younger plantations was also reported by Sangha and Jalota (2005).

5.3.1.3. Comparative evaluation

Exchangeable iron in plantations of eucalypt increased with rotation. However, in teak plantations an initial increase was followed by a decrease in the older plantations. When soils under plantations of teak and eucalypts over similar period of time were considered,

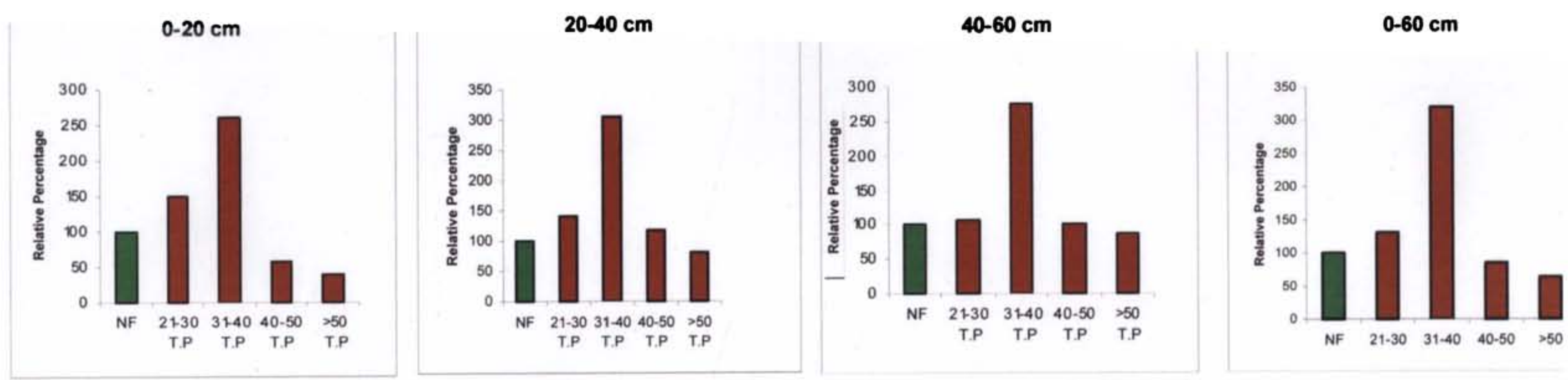

Fig.32 Relative mean values of exchangeable iron at different depths in natural forest and teak.

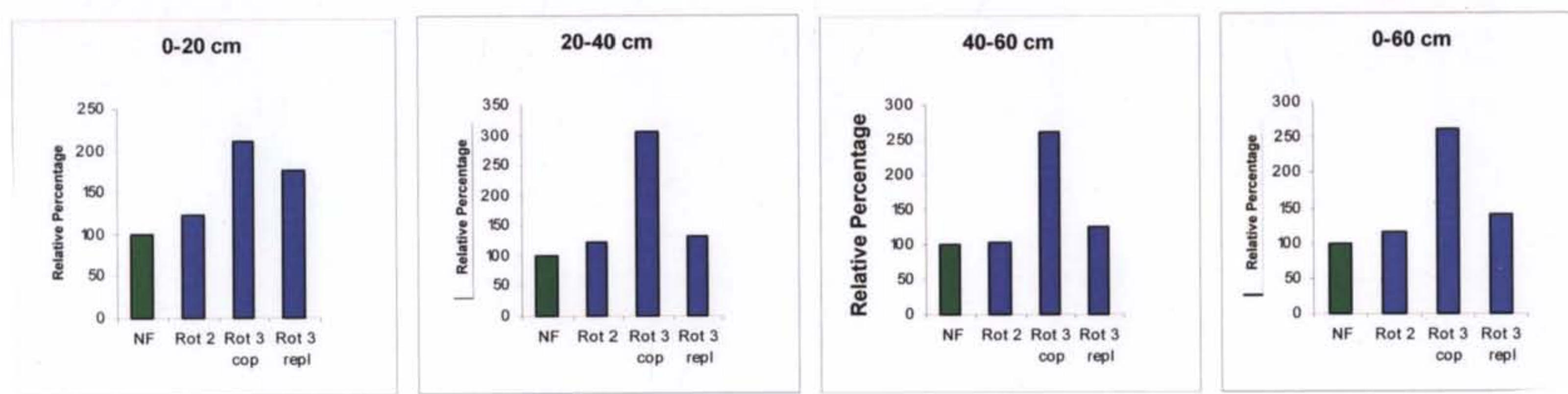

Fig.33 Relative mean values of exchangeable iron at different depths in natural forest and eucalypt plantations

it was observed that after 20-30Y, soils under eucalypts were richer in exchangeable iron than in natural forest by 15 per cent while those of teak plantations were richer by 31 per cent. After 30-40Y, soils under teak were richer than natural forest by 220 per cent while those under eucalypts were richer by 41 and 162 per cent, respectively.

Micronutrient concentration may be reduced by complexation with soil organics. particularly when metal organic complex has low solubility (Stevenson, 1991). In this case, exchangeable iron was found to be significantly and negatively correlated to organic carbon. The change in exchangeable iron status of plantation soils may be mediated through soil organic carbon. The pattern of change in exchangeable iron concentration was also seen to be related to organic carbon status of soil. Among teak plantations, relative availability of iron was highest in 31-40Y age class plantation soils. The lowest relative mean organic carbon values among teak plantations was also recorded in this age class. No significant difference was observed between soils of older teak plantations and natural forest in the 20-40 and 40-60cm depths in either organic carbon or exchangeable iron.

In plantations of eucalypts, iron content increased and organic carbon decreased with rotation. Among third rotation plantations, higher organic carbon and lower exchangeable iron was observed in replanted plantations when compared to coppiced one.

5.3.2. Exchangeable copper

5.3.2.1. Teak

The exchangeable copper in soils of natural forest varied from 0.27 to 0.92ppm and in plantations of teak, it varied from 0.40 to 2.89ppm. Amount of exchangeable copper in plantations of teak is significantly higher than that of natural forest. Within teak plantations, relative values of exchangeable copper in older plantation soils were lower than that of younger plantations.

In the 0-20cm soil depth, the mean values of exchangeable copper varied from 1.42 to 1.88ppm and the relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 384, 334, 220 and 240 per cent, respectively. Mean values of exchangeable copper in 20-40 and 40-60cm depths varied from 1.68 to 2.29ppm and from 1.28 to 1.98ppm.The relative mean values in these depths in 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 560, 409, 286 & 305 per cent and 340, 332, 252 & 325 per cent, respectively. Availability of copper in soils of teak plantations was significantly higher than natural forest in 0-20, 20-40 and 40-60cm depths.

In the 0-60cm depth, mean values of exchangeable copper in soils of teak plantations varied between 1.46 to 2.06ppm and the relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y plantations were 434, 370, 236 and 268 per cent, respectively. Karia and Kiran (2004) reported higher values for copper in the surface sample of a closed teak forest of Chhotaudepur.

5.3.2.2. Eucalypts

Exchangeable copper in natural forest varied from 0.76 to 5.29ppm while in plantations of eucalypt, it varied from 0.48 to 5.8ppm. In natural forest, exchangeable copper increases with depth. On the other hand, no trend was observed in eucalypt plantations. The mean values for exchangeable copper in eucalypt plantations were generally lower than the corresponding values in the natural forest. However, availability of copper in second rotation plantations was higher than that of natural forest in the 20-40cm depth though the difference was not significant.

Third rotation replanted plantation had lower amounts of exchangeable copper than coppiced plantations. In general, availability of copper in eucalypt soils was significantly lower than that in the natural forest. However, exchangeable copper in the 20-40cm depth in second rotation eucalypt plantations was higher than that in the natural forest. In the 0-20cm depth, it was observed that, mean values of exchangeable copper varied from 1.06 to 2.11ppm and the relative mean values of second, third and third rotation replanted plantation were 97, 81 and 49 per cent, respectively. In the 20-40 and 40-60cm depths, the mean values varied from 0.93 to 3.88ppm and from 0.9 to 2.36ppm. The relative

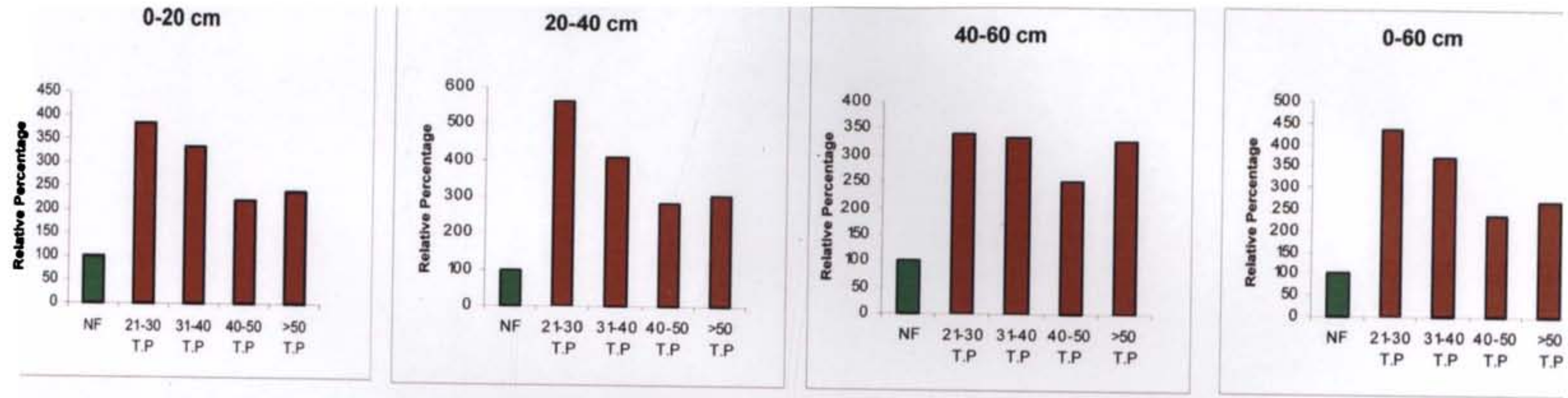

Fig.34 Relative mean values of exchangeable copper at different depths in natural forest and teak

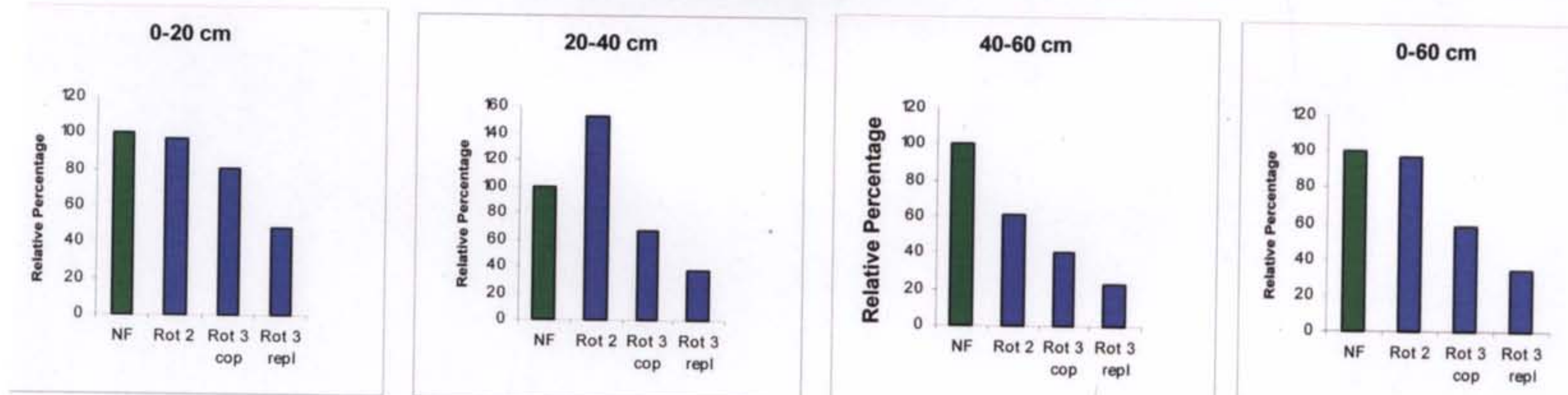

Fig.35 Relative mean values of exchangeable copper at different depths in natural forest and eucalypt plantations

mean values in the corresponding depths in second, third and third rotation replanted plantations were 152, 67 and 37 per cent and 61, 40 and 24 per cent, respectively.

In the 0-60cm depth, the mean values of exchangeable copper varied from 1.0 to 2.8 ppm and the relative mean values for second, third and third rotation replanted plantation were 97, 59 and 34 per cent respectively. Availability of copper in eucalypt plantations decreased with rotation in all the three depths. The difference between second rotation and third rotation replanted plantations was significant in all depths. On the other hand, a significant difference between second rotation and third rotation coppiced plantation was observed only in 20-40cm depth. Availability of copper in replanted plantations was lower than in coppiced ones though the difference was not significant.

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Baber *et al.* (2006) observed that copper in surface soil decreased as distance increased from the tree. This could be due to absorption of copper from soil by eucalypts. Lower copper availability in older eucalypt plantations when compared to younger plantations was reported by Sangha and Jalota (2005).

5.3.2.3. Comparative evaluation

The availability of soil copper to plants is relatively low which is favorable conditions as excessive availability leads to copper deposition on the roots and to stunted root systems. When exchangeable copper status in plantation soils was studied, contrasting pattern of variation from natural forest was observed in teak and eucalypt plantations. Soils of teak plantations were richer in exchangeable copper than natural forest whereas those of eucalypt were poorer. Higher extractable copper in plantations of teak as compared to soils under forest cover was also reported by Mongia and Bandyopadhyay (1992b). When soils under teak and eucalypt for similar periods of time were compared, it was observed that, after 20-30Y, soils of teak plantations were richer than natural forest by 334 per cent while those under eucalypts were poorer by 3 per cent. On comparing soils under teak and eucalypt in 30-40Y, it was noticed that soils under teak were richer in exchangeable copper than natural forest by 270 per cent while those under eucalypt were poorer by 42 to 66 per cent, respectively.

5.3.3. Exchangeable Zinc

5.3.3.1. Teak

Exchangeable zinc in natural forest soils varied from 0.46 to 2.80ppm and in teak plantations, it varied from 0.33 to 2.2ppm. In natural forest and plantations, the highest value for exchangeable zinc was recorded in the 0-20cm depth. Soils in the natural forest and teak plantations did not differ significantly in availability of zinc.

When soils in different age class teak plantations were compared, it was observed that zinc availability first increased and then decreased with age in 0-20cm depth. The mean values for exchangeable zinc in plantations of teak varied from 1.09 to 1.48ppm and the relative mean values in 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 75, 95, 85 and 76 per cent, respectively. The difference was significant in the oldest age class plantation. A significant decline in total zinc, in soils of Ist rotation, IInd rotation, IIIrd rotation teak plantations was reported by Dhanya *et al.* (2006). Although the study cannot be compared in tote, the trend observed, corroborated the findings of present study.

In 20-40 and 40-60cm depths, the mean values for exchangeable zinc varied from 0.78 to 1.29ppm and from 0.71 to 1.06ppm. The relative mean values in 20-40 and 40-60cm depths, in teak plantations of 21-30Y, 31-40Y, 41-50Y and >50Y age class were 89, 113, 164 and 106 per cent and 74, 110, 120 and 104 per cent, respectively. In 0-20cm depth, the highest relative mean value was recorded in 31-40Y age class plantations while in 20-40 and 40-60cm depths, the value was recorded in 41-50Y age class plantations.

In the 0-60cm depth, mean values of exchangeable zinc in plantations of teak varied from 0.86 to 1.21ppm and the relative mean values in 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 79, 104, 112 and 90 per cent, respectively. Availability of zinc in plantation soils initially increased and then decreased with age of plantations and the highest value for exchangeable zinc was recorded in 41-50Y age class plantations. Karia and Kiran (2004) reported similar values for zinc in the surface sample of a closed teak forest of Chhotaudepur.

5.3.3.2. Eucalypts

Exchangeable zinc, in soils of natural forest varied from 0.61 to 2.36ppm and in plantations of eucalypt, it varied from 0.55 to 6.04ppm. Zinc availability decreased with depth in soils of natural forest. This may be due to the enrichment of the upper portion of the solum due to the long term upper translocation by plant roots and subsequent incorporation into the surface layer of the soil through plant litter decay (Stevenson, 1991). A similar pattern was also observed in all plantations of eucalypts except third rotation replanted plantation. The disturbance to the soil during replanting might be responsible for the lack of said pattern in replanted plantation.

Soils in second rotation eucalypts had higher zinc availability than that of natural forest in 0-20, 20-40 and 40-60cm depths. However, the difference was significant only in 0-20cm depth. Soils in third rotation plantations were poorer in exchangeable zinc when compared with forest soils. It was also observed that availability of zinc decreased with rotation. Baber *et al.* (2006) observed that zinc in surface soil decreased as distance increased from the tree. This could be due to absorption of zinc from soil by eucalypts.

On comparing the 0-20 and 20-40cm depths in different rotation eucalypt plantations, it was observed that mean values of exchangeable zinc in plantations of eucalypt varied from 1.57 to 3.6ppm and from 0.84 to 1.81ppm. The relative mean values of second, third and third rotation replanted plantations for these were 166, 90 and 73 per cent and 153, 72 and 64 per cent, respectively. A significant decline in availability of zinc with rotation was observed in 0-20 and 20-40cm depths.

Among third rotation plantations, higher values were seen in coppiced plantations than replanted ones, though the difference was not significant. Soils in 40-60cm depth had exchangeable zinc varying from 0.85 to 1.81ppm and the relative mean values of second, third and third rotation replanted plantation were 147, 71 and 152 per cent, respectively.

Soils in the natural forest and eucalypt plantations did not differ significantly from each other at this depth. In the 0-60cm depth, the mean values for exchangeable zinc varied from 1.2 to 2.4ppm and the relative mean values for second, third, third rotation replanted plantations were 158, 80 and 91 per cent, respectively. Sangha and Jalota (2005) reported a decrease in Zn availability with age in eucalypt plantations.

5.3.3.3. Comparative evaluation

Exchangeable zinc in teak plantations initially increased and then decreased with age while in plantations of eucalypt, a decline with rotation was observed. On comparing soils under teak and eucalypts for 20-30Y, it was observed that soils under teak had 25 per cent less exchangeable zinc than natural forest, while those under eucalypt had 58 per cent higher values. After a period of 31-40Y under plantations, it was observed that teak were richer than natural forest by four per cent and those of eucalypts were poorer by 9-20 per cent. Zinc exhibited significant positive correlation with exchangeable base, organic carbon and exchangeable magnesium. Significant positive correlation of zinc with organic carbon has been previously reported by Sakal *et al.* (1988) and Shetty *et al.* (2006).

5.3.4. Exchangeable Manganese

5.3.4.1. Teak

Exchangeable Manganese in soils of natural forest varied from 11 to 55.2ppm while in plantations of teak it varied from 5.3 to 117.0ppm. Availability of manganese in soils of natural forest and plantations generally decreased with depth.

On comparing soils in 0-20cm depth in plantations of teak, it was observed that, exchangeable manganese was higher in younger teak plantations than both older plantations and natural forest. The mean values of teak plantations varied from 31.5 to 79ppm and the relative mean values in 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 203, 137, 70 and 86 per cent, respectively. The values reported by Karia and Kiran (2004) from the soils of closed teak forest of Chhotaudepur were similar to the values obtained from older teak plantations in the present study and lower than the values from younger teak plantations.

In 20-40cm and 40-60cm depths, exchangeable manganese in soils of teak plantations varied from 16.1 to 31.6ppm and from 14.3 to 28.89ppm. The relative mean values in 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 149, 107, 66 and 129 per cent and 210, 100, 84 and 170 per cent, respectively.

Soils in natural forest and plantations of teak did not differ significantly in manganese availability. The only exception was the oldest age class teak plantation. Soils of >50Y age class teak had significantly higher manganese content than natural forest in 20-40 and 40-60cm depths.

In the 0-60cm depth, mean values for exchangeable manganese in teak plantations varied from 20.68 to 52.53ppm and the relative mean values in the 21-30Y, 31-40Y, 41-50Y and >50Y age class plantations were 191, 119, 72 and 115 per cent, respectively. Plantations of teak were generally richer in exchangeable manganese than those of natural forest although this was not true in the case of 41-50Y age class plantations.

5.3.4.2. Eucalypts

Exchangeable manganese in soils of natural forest varied from 10.9 to 83.0ppm while in eucalypt soils, the values varied from 9.3 to 81.3ppm. Availability of manganese in natural forest decreased with depth. Availability of manganese in soils of eucalypt plantations was significantly lower than that of natural forest in 0-20cm depth. When soils in 0-20, 20-40 and 40-60cm depths in plantations of eucalypt were studied, it was observed that exchangeable manganese decreased with rotation although the decrease was significant only at 20-40cm depth. The mean values in 0-20 and 20-40cm depth varied between 23.8 to 42.6ppm and from 17.5 to 50.9ppm.The relative mean values for second, third and third rotation replanted plantations were 64, 41 and 36 per cent for 0-20cm and 140, 57 and 48 per cent in 20-40cm depth. The mean values in this depth in eucalypt plantations varied from 14.2 to 49.4ppm and the relative mean values in second, third, and third rotation replanted plantations were 148, 79 and 43 per cent, respectively.

In the 0-60cm soil layer, soil exchangeable manganese decreased with rotation. The mean values of exchangeable manganese varied from 18.5 to 47.6ppm and the relative mean

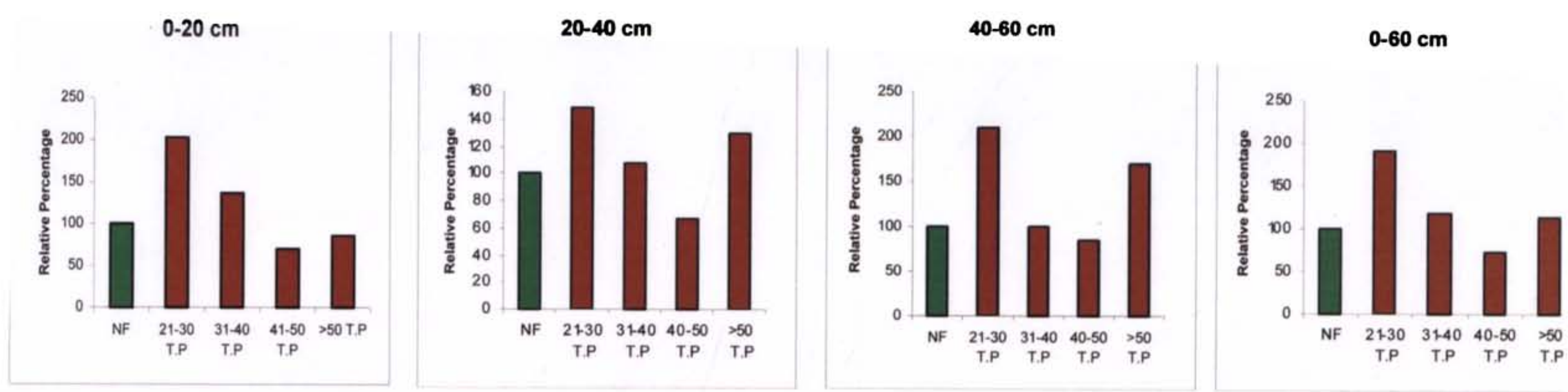


Fig.38 Relative mean values of exchangeable manganese at different depths in natural forest and teak.

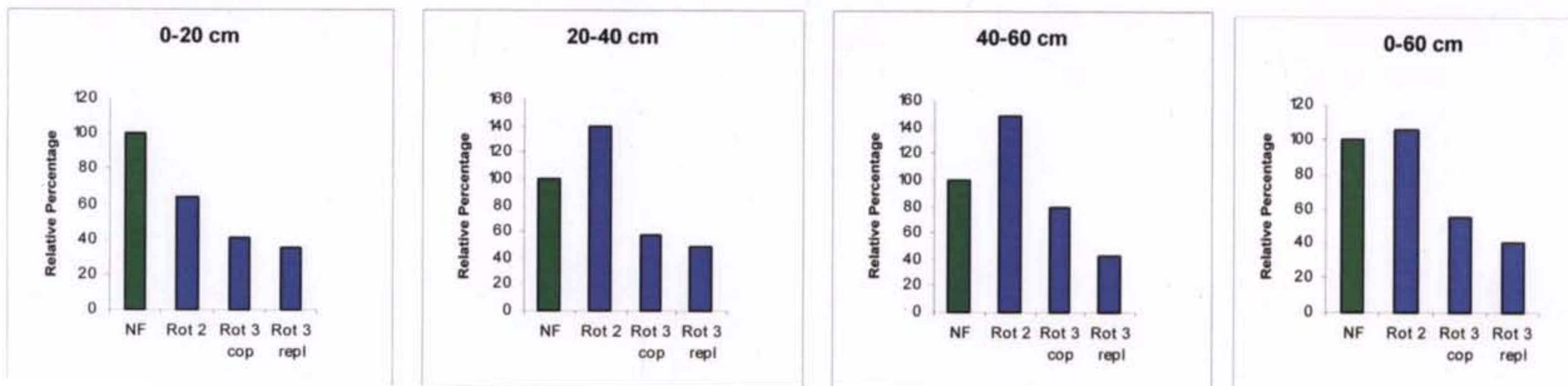


Fig.39 Relative mean values of exchangeable manganese at different depths in natural forest and eucalypt plantations

values of exchangeable manganese in second, third and third rotation replanted plantations were 105, 55and 41 per cent, respectively. Among third rotation plantations, lower values were recorded in replanted plantations.

Lower availability of manganese in older eucalypt plantations was also observed by Sangha and Jalota (2005). Baber *et al.* (2006) observed that manganese in surface soil decreased as distance increased from the tree. This could be due to absorption of manganese from soil by eucalypts.

5.3.4.3. Comparative evaluation

Availability of manganese in eucalypt plantation soils decreased with rotation. In plantations of teak, such a clear pattern was not seen. On comparing soils under teak and eucalypts for similar periods, it was observed that after 20-30Y, the soils under teak and eucalypts were richer than natural forest by 91 per cent and 5 per cent, respectively. When soils under teak and eucalypts plantations for 31-40Y were compared, it was noticed that those under teak were richer than natural forest by 19 per cent while soils under eucalypts were poorer by 45 to 59 per cent, respectively. Exchangeable manganese was positively correlated with organic carbon and total nitrogen. Positive correlation of exchangeable manganese with organic carbon was earlier reported by Sakal *et al.* (1988) and Shetty *et al.* (2006). Total nitrogen is significantly and positively correlated to organic carbon. Hence the correlation of exchangeable manganese with total nitrogen may be mediated by its relationship to organic carbon.

Chapter 6

Organic Matter Fractions

6.1. Introduction

Monoculture plantations differ from natural forest, and from each other, in quantity of litter, its nutrient content and rate of decomposition. Conversion of natural forest to monoculture plantations results in replacement of mixed litter of a natural forest with uniform litter of plantations and is accompanied by changes in the microclimate. The changes in quantity, quality and rate of decomposition of litter alters the amount and nature of organic matter in soil.

Among plantations of teak and eucalypts, the annual amounts of leaf litter added were higher in teak than in eucalypts (Singh *et al.*, 1993). Teak litter also decomposed rapidly when compared to eucalypts litter and the decay rate varied significantly both in the field and laboratory (Singh *et al.*, 1993, Pande and Sharma, 1993a, Sankaran, 1993, Maharudrappa *et al.*, 2000, Panda and Swain, 2002). The release of carbon from teak litter was lower than that of eucalypts litter (Panda and Swain, 2002).

The chemical composition of litter also changes. Eucalypts leaves are waxy in nature and contain fatty acids (Singh and Das, 1992). Pande (1999) found that ether soluble extractives (fats and waxes), alcohol soluble extractives (resin) and hot water soluble extractives (free sugars) were richer in leaves and twigs of eucalypts than teak. On the other hand lignin content of teak leaves was greater than that of eucalypts.

Thus, it is reasonable to expect that surface soils with similar parent materials, ground cover and topography but with different vegetation types differ in their soil properties. Similar findings were reported by Singh *et al.* (1988). The conversion of natural forest to monoculture plantations not only affect the chemical properties and nutritional status of soil under it (Mongia and Bandyopadhyay, 1992a; Balagopalan 1995a; Balagopalan 1995b; Dagar *et al.*, 1995; Michelsen *et al.*, 1996; Joshi *et al.*, 1997; Lian and Zhang, 1998; Aweto 2001; Pande, 2004; Guo -Jian Fen *et al.*, 2004) but also has an effect on the composition of soil organic matter (Wang, 1967, Singhal and Sharma, 1983, Balagopalan, 1991, Balagopalan, 1995a).

6.2. Materials and Methods

Five surface samples, each from natural forest, teak and eucalypts were subjected to proximate analysis for determining the components by the methods of Stevenson (1965). The proximate components estimated were fats, waxes and oils, resins, free sugars, hemicellulose, cellulose, lignin and protein.

6.2.1. Fats, waxes and oils

Fifty gram of soil was extracted with 100ml ether in soxhlets apparatus for 24h. Evaporated the ether extract to a small volume, and transfered the solution to a preweighed weighing bottle. Dried it to a constant weight in an oven at 100°C. Transfered to a desiccator; allowed to cool and reweighed the weighing bottle (Stevenson, 1965).

Per cent of fat, waxes and oils = $(W_2-W_1) \times 100/50$

Where W_1 = weight of empty weighing bottle

W_2 = weight of weighing bottle after cooling

6.2.2. Resins

Transfered the ether extracted soil to a 500ml flask, add 100ml of ethyl alcohol, and heated the mixture under steam bath under reflux for 2h. Filtered off hot alcohol using a Buchner funnel, using Whatman No. 50 filter paper. Washed the soil thoroughly with hot alcohol, combined the filtrate and washings, and evaporated off the bulk of alcohol on a steam bath. Transfered the extract quantitatively to a weighed evaporating dish, using several small washes of ethyl alcohol. Evaporated off the solvent of a steam bath, dry the residue in an oven at 100°C and reweighed the evaporating dish after cooling in a desiccator (Stevenson, 1965).

Per cent of resin = $(W_2-W_1) \times 100/50$

Where W_1 = weight of empty evaporating dish

W_2 = weight of evaporating dish after cooling

6.2.3. Free sugars

Added 100 to 200ml of distilled water to ether – alcohol- extracted soil, and boil the mixture under reflux for two hours. Centrifuged the sample, decanted and washed the residue thoroughly with hot water, and adjusted the volume of filtrate and washings to one liter. Poured 200ml of this solution to an evaporating dish; evaporated off the water on a steam bath, dried the residue in an oven at 100°C for 30 minutes. Cooled in a desiccator, weighed the evaporating dish and placed in a muffle furnace at 550°C until all the organic matter has burned off. Cooled in desiccator and reweighed the evaporating dish (Stevenson, 1965).

Per cent free sugars = $[(W_2-W_1) \times 100 \times 200] / (50 \times 1000)$

Where W_1 = weight of evaporating dish after drying in oven

W_2 = weight of evaporating dish after burning off organic matter

6.2.4. Hemicellulose

Placed the residue with hot water extract in an oven, and dried it at 100°C. Transfered half of this residue to one liter flask. Added 300ml of hydrochloric acid solution (56ml concentrated hydrochloric acid in one liter distilled water) and boiled the mixture for five hours under reflux. Cooled, filtered through No. 50 Whatmann filter paper, washed the residue thoroughly with hydrochloric acid solution and adjusted filtrate plus washings to 500ml. Added 25ml aliquot of this solution to 125ml Erlenmeyer flasks. To this added two drops of bromo cresol purple indicator followed by sodium hydroxide solution (25g sodium hydroxide in one liter distilled water) until colour turns purple. Allowed the flask to stand for several hours with frequent shaking. Filtered and washed residue thoroughly with distilled water and adjusted the volume of filtrate to 100ml. To this added excess of Felhing solution (usually 10ml), bring the mixture to boil and added 3-5 drops of methylene blue indicator and titrated against standard glucose solution (2g of pure glucose in one liter of distilled water). The standard glucose solution was added at 5ml increment at 20s intervals until the blue colour disappeared. From this rough titration value, titrated the second sample by adding as much of the standard glucose as possible before boiling commenced. Then added the final 0.3 to 1ml of standard glucose solution at such a rate that the end point was reached within three minutes after boiling starts.

Performed a blank titration using the same quantity of Felhing's solution (Stevenson, 1965).

$$\text{Per cent Hemicellulose} = \frac{(T.V_{blank} - T.V_{sample}) \times 2 \times 0.9 \times 500 \times 50 \times 2}{25 \times (\text{wt. of sample taken for analysis})}$$

6.2.5. Cellulose

Transfered the soil residue (obtained after hydrolysis with hydrochloric acid) to a weighed evaporating dish and dried in an oven at 100°C and reweighed the evaporating dish. Ten gram of residual soil was taken in a stoppered 100ml conical flask and added 25ml of sulphuric acid solution (83.4 ml of concentrated sulphuric acid in 100ml of distilled water). Allowed the soil to stand for 2.5 h. at 12 to 14°C. Transfered to one liter flask and added 875ml of distilled water and boiled for five hours under reflux. Cooled, filtered through No. 50 filter paper. Adjusted filtrate and washing to 1L and estimated the amount of reducing sugars in solution as above (Stevenson, 1965).

$$\text{Per cent of Cellulose} = \frac{(T.V_{blank} - T.V_{sample}) \times 2 \times 0.9 \times 1000 \times 50 \times 2)}{25 \times (\text{wt. of sample taken for analysis})}$$

6.2.6. Protein

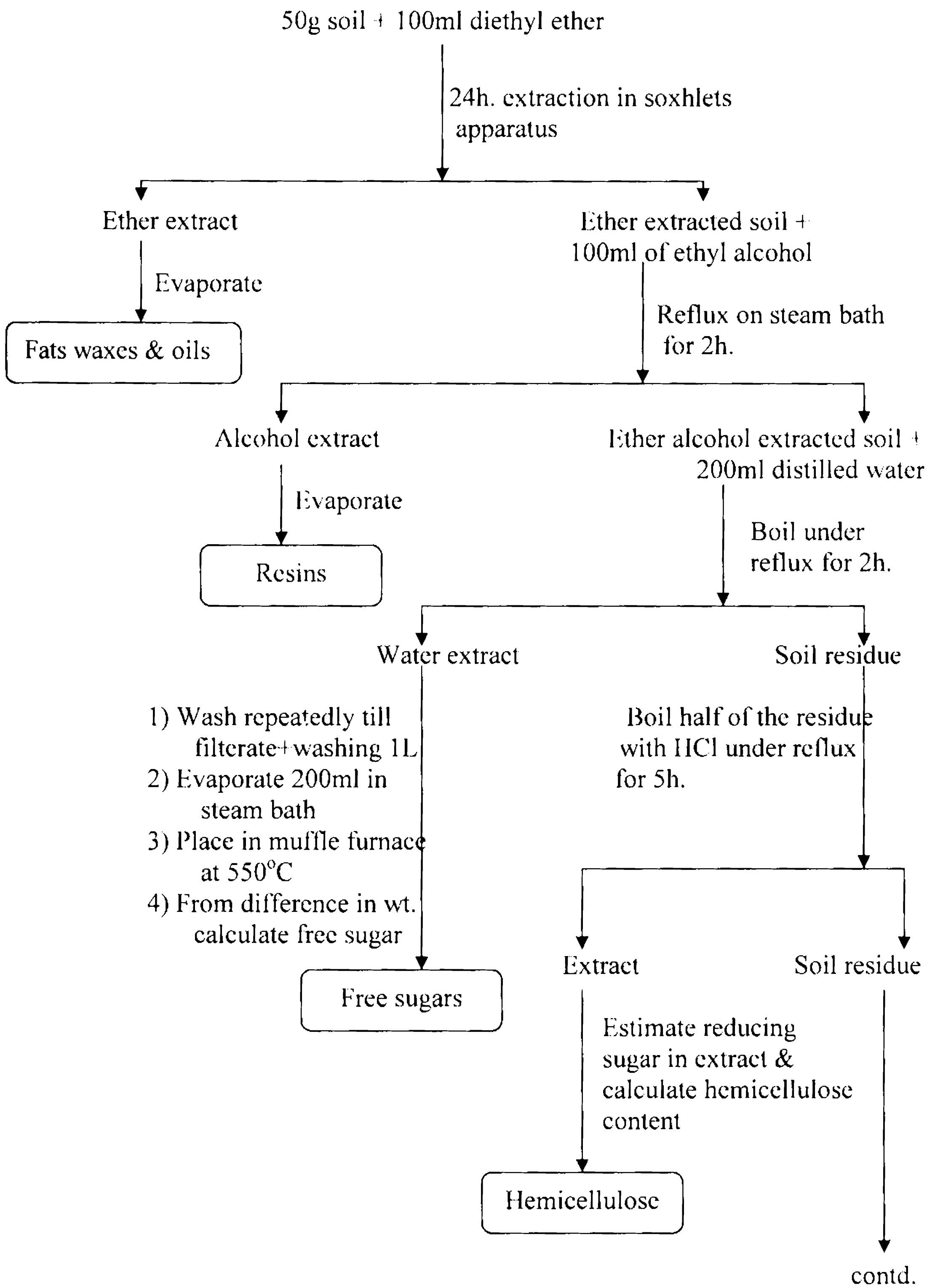
Transfered the soil residue from filter paper to a weighed evaporating dish, dried in an oven at 100°C and reweighed it. Analyzed one gram of the residue for total carbon and nitrogen. Protein was calculated by multiplying the nitrogen content in the soil residue by a factor of 6.25 (Stevenson, 1965).

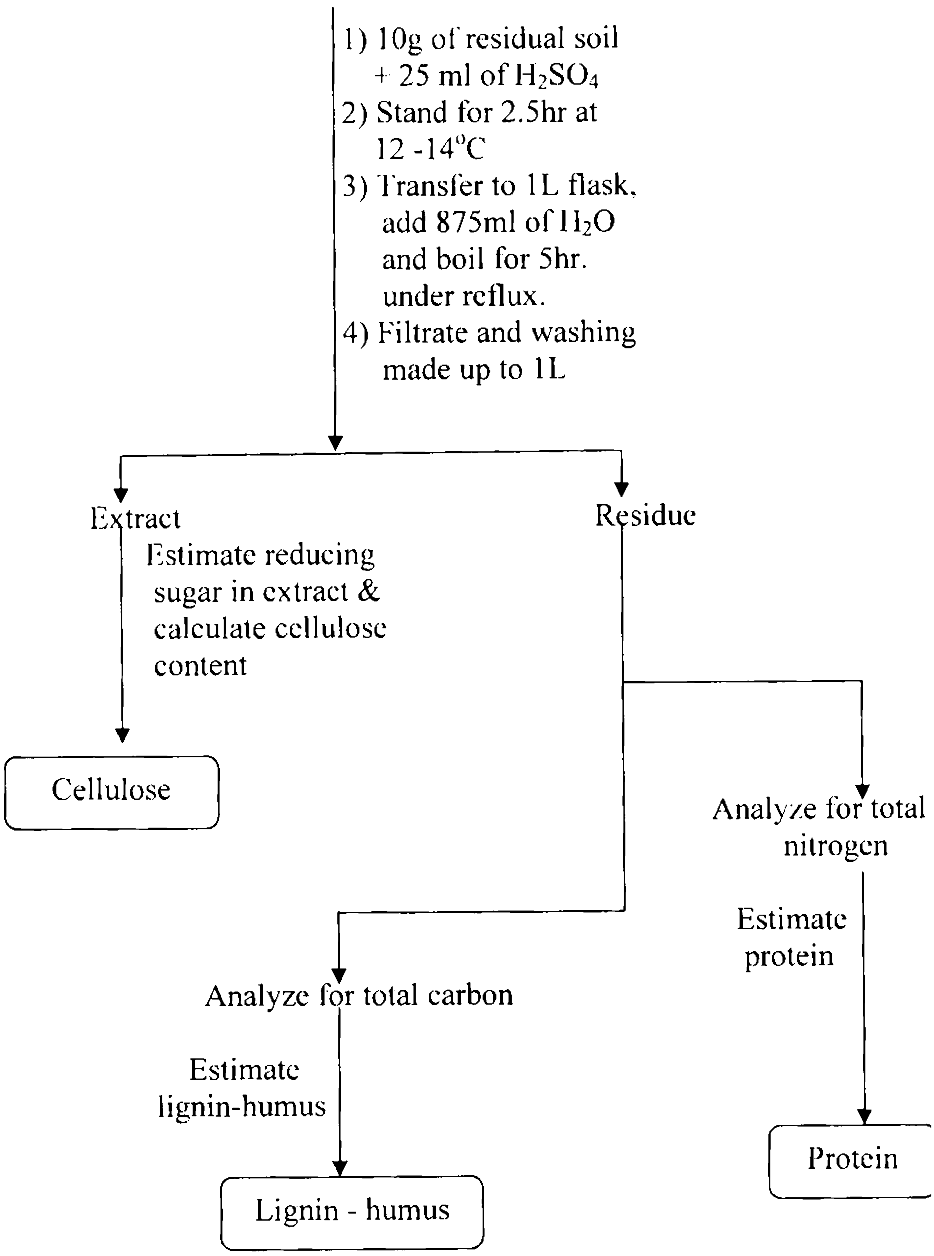
Per cent of Protein = (Nitrogen content x 6.25 x 50) x 2

6.2.7. Lignin – humus

Lignin humus content of soil was estimated by subtracting the value from total organic matter in the sulphuric acid residue (Stevenson, 1965).

Per cent of Lignin -humus =[(Carbon content x 1.724)-(Nitrogen content x 6.25)] x50 x 2


50g soil + 100ml diethyl ether
24h. extraction in soxhlets apparatus
Ether extract
Evaporate
Fats waxes & oils
Ether extracted soil + 100ml of ethyl alcohol
Reflux on steam bath for 2h.
Alcohol extract
Evaporate
Resins
Ether alcohol extracted soil + 200ml distilled water
Boil under reflux for 2h.
Water extract
1) Wash repeatedly till filtrate+washing 1L
2) Evaporate 200ml in steam bath
3) Place in muffle furnace at 550°C
4) From difference in wt. calculate free sugar
Free sugars
Soil residue
Boil half of the residue with HCl under reflux for 5h.
Extract
Estimate reducing sugar in extract & calculate hemicellulose content
Hemicellulose
Soil residue
contd.


1) 10g of residual soil + 25 ml of H_2SO_4
2) Stand for 2.5hr at 12 -14°C
3) Transfer to 1L flask, add 875ml of H_2O and boil for 5hr. under reflux.
4) Filtrate and washing made up to 1L
Extract
Residue
Estimate reducing sugar in extract & calculate cellulose content
Cellulose
Analyze for total nitrogen
Estimate protein
Protein
Analyze for total carbon
Estimate lignin-humus
Lignin - humus

6.2.8. Statistical analysis

The data were analyzed statistically with SPSS software and t-test was done for pair wise comparison.

6.3. Results and Discussion

The mean values of soil proximate constituents in natural forest and plantations of teak and eucalypts are described in Table.10. Results of ANOVA and t-test for different soil parameters of Vazhachal Division and the result of ANOVA and t-test for different soil parameters in Thrissur Forest Division are given in appendix 77. Correlation between proximate constituents is given in appendix 78.

6.3.1. Fats and waxes

The amount of fats and waxes in plantations of teak varied from 0.016 to 0.032 per cent and in natural forest, the values ranged from 0.040 to 0.05 per cent. In plantations of eucalypts, the quantity of fats and waxes varied from 0.024 to 0.04 per cent and in the adjacent natural forest, the amount varied from 0.056 to 0.069 per cent. The fats and waxes in soils of monoculture plantations were significantly lower than that of natural forest. The relative mean value in teak plantations was 54 per cent while in plantations of eucalypts, it was 47 per cent. In natural forest, fats and waxes constitute 1.5 per cent of total organic carbon. On the other hand, in teak and eucalypt plantations, 1.0 and 1.2 per cent of organic carbon in soil is made up of fats and waxes.

6.3.2. Resins

Soils in eucalypt plantations had higher resin contents than both natural forest and plantations of teak. In eucalypt plantations, resins varied from 0.111 to 0.137 per cent whereas in the adjacent natural forest, the quantity varied from 0.056 to 0.069 per cent. Resin content in soils of teak plantations varied from 0.016 to 0.032 per cent while in the natural forest in the same location, the quantity varied between 0.04 to 0.05 per cent. Resin content in soils of natural forest differed significantly from those in teak and eucalypt plantations. The relative mean resin values for teak and eucalypt plantations,

Table 9. Mean value of soil proximate constituents in natural forest and plantations of teak and eucalypt

Proximate Constituents	Study area			
	Vazhachal		Thrissur	
	Natural forest	Teak	Natural forest	Eucalypts
	-----------%-----------		-----------%----------	
Fats and Waxes	0.045	0.025	0.065	0.031
Resins	0.045	0.023	0.063	0.124
Free sugars	0.036	0.021	0.048	0.030
Hemicellulose	0.347	0.282	0.511	0.322
Cellulose	0.086	0.055	0.119	0.048
Lignin - humus	1.044	0.829	1.491	0.832
Protein	0.814	0.728	1.142	0.716

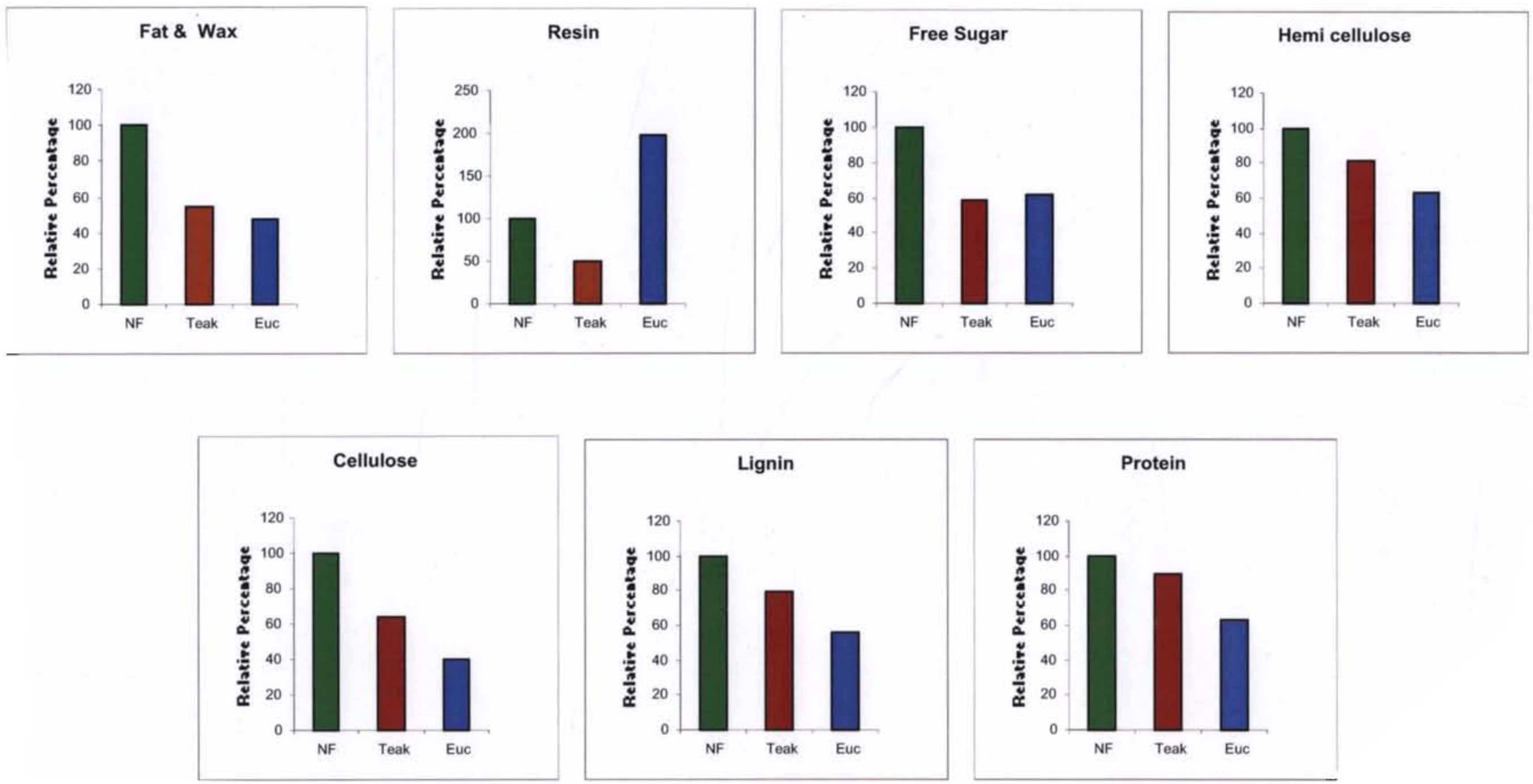


Fig.9. Relative mean values of soil organic fractions in surf ace layer of natural forest,teak and eucalypt plantations.

compared to natural forest, were 50 and 199 per cent, respectively. In the natural forest, contribution of resin to soil organic carbon was 1.5 per cent whereas in plantations of teak and eucalypt, it was 0.9 and 4.7 per cent, respectively. Singhal (1986) reported higher contents of resins in soils under eucalypts compared to Sal. Higher resin content in soils of eucalypts compared to natural forest was also reported by Balagopalan (1991).

6.3.3. Free Sugars

Free sugar contents in soils of natural forest was significantly higher than those in plantations of teak and eucalypt. The amount of free sugar in soils of teak plantations varied from 0.018 to 0.024 per cent and in the adjacent natural forest, it varied from 0.035 to 0.038 per cent. In plantations of eucalypt, free sugar in soil varied between 0.024 to 0.037 per cent while the analogous values for adjacent natural forest were 0.04 to 0.052 per cent, respectively. The relative mean value of free sugars in plantations of teak and eucalypts were 59 and 62 per cent, respectively. Lower free sugars in plantation soils corroborates the findings of Dalal and Henry (1988). In natural forest and eucalypts plantations, free sugars contribute to 1.1-1.2 per cent of soil organic carbon. On the other hand, contribution of free sugar to organic carbon in teak soils was slightly lower *viz.*, 0.88 per cent.

6.3.4. Hemicellulose

Soils in the natural forest were the richest in hemicellulose and eucalypt soils had the lowest values. Hemicellulose in soils of natural forest and adjacent teak plantations varied from 0.330 to 0.378 per cent and from 0.260 to 0.313 per cent, respectively. Hemicellulose in eucalypt and adjacent forest soils varied from 0.294 to 0.352 per cent and from 0.482 to 0.535 per cent, respectively. Hemicellulose contents in plantation soils were significantly lower than those in natural forest. The relative mean values of hemicellulose in soils of teak and eucalypt plantations were 81 and 63 per cent, respectively. The contribution of hemicellulose component to organic carbon did not differ much between plantations and forest soils. Hemicellulose constituted nearly 11-12 per cent of organic carbon in soil.

6.3.5. Cellulose

The quantity of cellulose in soils varied from 0.074 to 0.112 per cent in forest and 0.048 to 0.063 per cent in teak plantations. In plantations of eucalypt, cellulose content varied from 0.045 to 0.052 per cent. In the adjacent natural forest, cellulose varied from 0.114 to 0.126 per cent. Plantations of teak and eucalypt differed significantly from natural forest in the amount of cellulose. The relative mean values of cellulose in teak and eucalypt plantations were 64 and 40 per cent, respectively. Lower content of cellulose in soils under eucalypts compared to Sal was also reported by Singhal (1986).

The contribution of cellulose towards organic carbon was lower in plantation soils than in natural forest. The contribution of cellulose towards organic carbon in soils of natural forest was 2.8-2.9 per cent. In teak and eucalypts plantations it was lower, *viz.*, 2.26 to 1.80 per cent, respectively.

6.3.6. Lignin - humus

Soils in the teak and eucalypt plantations had significantly lower lignin - humus contents than those in the natural forest. Lignin - humus contents in teak soils varied from 0.780 to 0.904 per cent while in the adjacent natural forest, the variation was from 1.019 to 1.058 per cent, respectively. Lignin - humus contents in eucalypt soils varied from 0.775 to 0.901 per cent and in the adjacent natural forest, the values varied between 1.427 to 1.579 per cent. The relative mean values of teak and eucalypt plantations were 79 and 56 per cent, respectively. Lower content of lignin - humus in soils under eucalypts compared to Sal was also reported by Singhal (1986).The contribution of lignin - humus towards organic carbon in soil was similar for natural forest and teak. Lignin - humus made up nearly 35 per cent of soil organic carbon in natural forest and 34 per cent in teak plantations. On the other hand, in plantations of eucalypt, lignin - humus constituted 31 per cent of total organic matter.

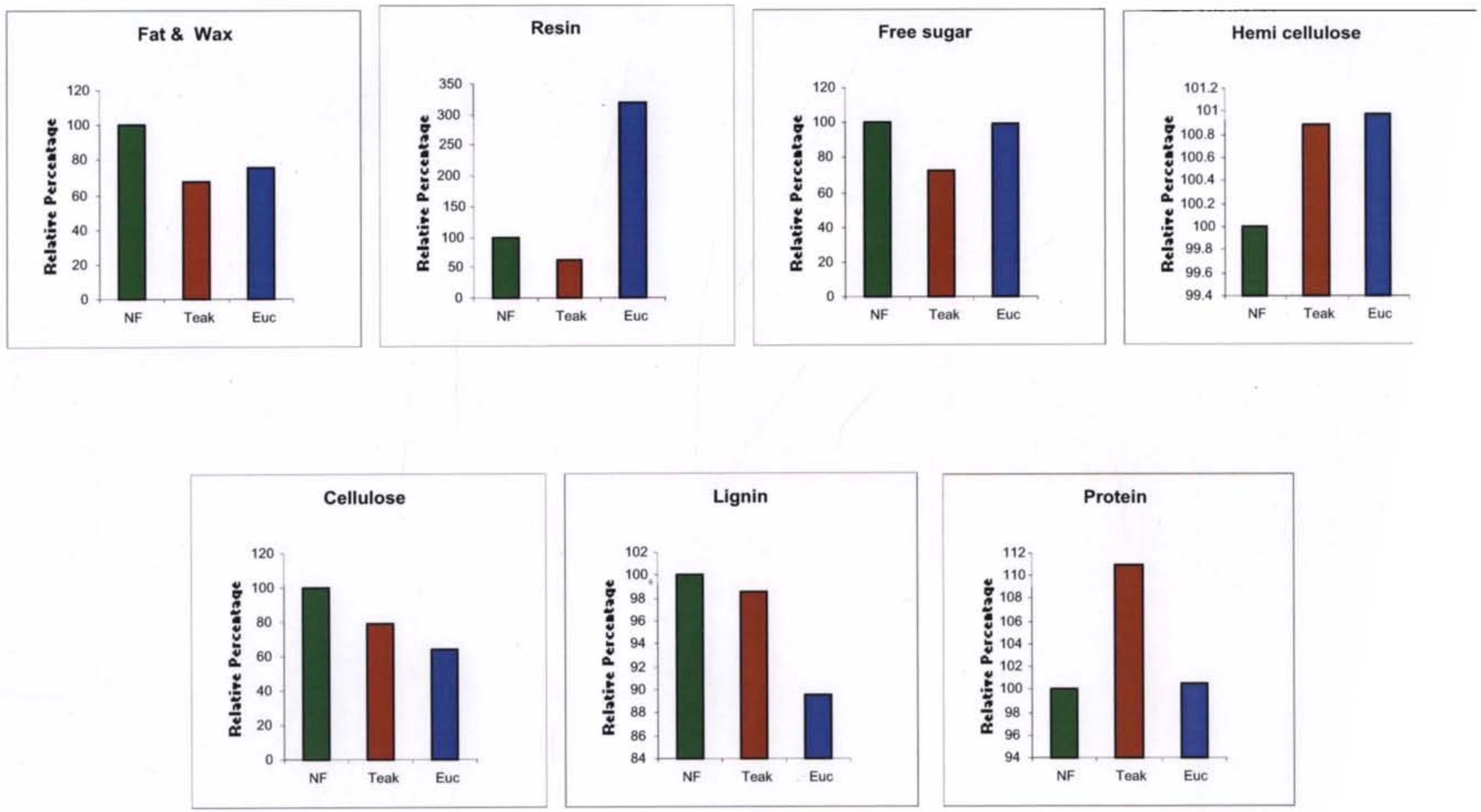


Fig.4. Relative contribution of organic fract ions to soil organic carbon in natural forest,teak and eucalypt plantations.

6.3.7. Protein

Soils in the natural forest were richest in protein while those in eucalypt had the lowest amount. The values in teak plantations varied from 0.679 to 0.784 per cent. In the adjacent natural forest, protein contents in soils varied between 0.768 to 0.856 per cent. In eucalypt plantations, protein contents in soils varied from 0.660 to 0.776 per cent and in the adjacent natural forest, protein varied from 1.098 to 1.182 per cent. The relative mean values of teak and eucalypt plantations were 89 and 63 per cent, respectively. The quantity of protein in soils of teak and eucalypt plantations differed significantly from that of natural forest. Protein made up 27 per cent of soil organic mater in forest and plantations of eucalypt while in teak plantations, the value was slightly higher, 30 per cent.

6.3.8. General Discussion

Proximate constituents play an important role in many soil properties. Some organic compounds are known to possess stimulatory or phytotoxic effects in soils (Braids and Miller, 1975; Ghosh and Bhardwaj, 2002). They are also known to influence the physical and chemical properties of soils. For example, soil lipids, by their orientation on the surface of soil particles, may affect the decomposition of soil organic matter and subsequent mineralization of plant nutrients. As they are distinctly hydrophobic, they could be expected to alter soil aggregate stability and degree of wetting. Soil waxy materials may waterproof soil particles, thereby, limiting the free solution of soil nutrients for plant growth and microbial activity (Greig and Smith, 1910). Polysaccharides in soil exert an important influence on aggregate stability and thereby on air and water movement in soil and are especially important in soils of low organic matter content (Green land and Oades, 1975).

Among the proximate constituents, the contribution of lignin-humus towards the total organic carbon was the greatest in all the three ecosystems studied. This may be due to the slow rate of degradation of lignin. Most organic materials, when added to soils, will rapidly decompose under aerobic conditions. The rate at which decomposition occurs is very dependent on the physical state and composition of organic material, and the precise soil conditions. In general, decomposition proceeds most rapidly in soils, close to their field capacity, whose temperature are between 25°C 35°C, having pH between 5 and 8 and supplied with adequate nutrient ions. Among the organic compounds added to soils, the decomposition of glucose proceeds most rapidly followed by that of starch, which decomposes more rapidly than cellulose. Lignin is broken down very slowly (Greenland and Oades, 1975). As a result, the concentration of lignin among proximate constituents in soil may be expected to be the highest. This was also true in the present study. The per cent of lignin-humus in soil organic fraction was the highest compared to other proximate constituents. It varied from 35 per cent in natural forest to 31 per cent in eucalypt plantations.

In natural forest, teak and eucalypt plantations, the smallest fraction isolated (quantitatively) was free sugars. This is not surprising, considering the rapidity with which they are likely to be utilized by microorganisms being the most important material readily available as an energy substrate. The content of cellulose and hemicellulose in soils was greater than that of free sugars, fats and waxes. This is not only due to its moderate resistance to break down, but also, because most of the carbohydrate added to the soil is in the form of cellulose. The content of hemicellulose in soil was greater than that of cellulose. This is explained by the fact that the rate of disappearance of hemicellulose is initially greater and subsequently slower than that of cellulose It is also likely that newly synthesized hemicellulose produced by microorganisms was more resistant to decomposition (Waksman and Hutchings, 1935; Ashworth, 1942).

Soils in teak and eucalypt plantations differed significantly from soils of natural forest in the content of proximate organic constituents. The proximate constituents *viz.*, fats and waxes, free sugar, hemicellulose, cellulose, lignin and protein in soils of monoculture plantations were significantly lower than that of natural forest. As the proximate constituents are derived from organic matter, the trend observed with respect to organic carbon in plantations is followed in toto for the proximate constituents. This supposition is also supported by the significant and strong intercorrelation observed between proximate constituents and organic carbon. Also, it was observed that all the proximate constituents were strongly and significantly correlated among themselves with the exception of resin (Appendix 60). Resin was poorly correlated with other proximate constituents. Similar findings were reported by Balagopalan (1991).

Soils in eucalypt plantations had higher resin contents than both natural forest and plantations of teak. However, significantly higher resin contents was observed in eucalypt plantations compared to teak and natural forest. This can be attributed to the resinous nature of eucalypt leaf litter. These observations are in concurrence with the findings of Singhal (1986), Singh and Singhal (1974) and Balagopalan (1991).

Chapter 7

Factor Analysis and Fertility Index

7.1. Introduction

The classical method of studying the changes in soils is by estimating various properties of soils *viz*., physical properties (texture, bulk density, particle density, porosity etc.) chemical properties (pH, exchangeable bases) and nutrient status (Organic carbon, nitrogen, phosphorus, potassium, calcium, magnesium, iron, copper, zinc, manganese etc.). These values were then subjected to statistical tools like analysis of variance, correlation, regression etc. Many of these properties are correlated and measure aspects of the same underlying dimensions or *factors*. In this scenario, Factor analysis is an extremely valuable tool that allows us to reduce a data set from a group of interrelated variables into a smaller set of uncorrelated factors. It explains the maximum amount of common variance in a correlation matrix using the smallest number of explanatory concepts (Field, 2000).

Although factor analysis helps to explain the variation in soil properties, it does not give a clear picture regarding the extent of degradation or recovery of soil consequent to plantation activity. Soil fertility index is a valuable tool in this context. Soil fertility is defined in terms of the capacity of soil to supply essential nutrients and water for the growth of plants (Aweto, 1981). Thus, the fertility status of soils under natural forest and plantations can be measured in terms of the concentration of exchangeable nutrients and water holding capacity. By relating the values of these properties in plantation soils to that of natural forest, the extent of degradation, if any, in soils of plantations can be assessed.

7.2. Factor analysis

Factor analysis is a multivariate method which takes into account the correlation among the variables. Multivariate statistical analysis is the simultaneous analysis of observations on several correlated variables. A series of univariate statistical analysis carried out separately for each of the variables, in general, is not adequate as it ignores the correlation among the variables. It may even be misleading. On the contrary, multivariate analysis can throw light on the relationships, interdependence and relative importance of the characteristics involved and can yield more meaningful information (James and McCulloch, 1990).

Factor analysis is used in reducing the dimension of the problem i.e. from a large number of characters to a few linear combinations, known as factors, which are physically interpretable and also retain as much information as possible about the original set of variables. The analysis can reveal relationships, not previously suspected, and allow interpretations that would not ordinarily result from univariate analysis (Johnson and Wichern, 1992).

Factor analysis was used by various workers like Jha *et al.* (2000), Rugmini and Balagopalan (2004, 2006) to reduce the number of variables that explains the difference or similarities between soils under different vegetational cover and management. Jha *et al.* (2000) identified a four factor model as the underlying factor pattern on soil chemical properties in five plantations. The four factors identified were aggrading factor, sodium factor, phosphorus factor and total phosphorus factor. However, these factors were not used to differentiate between plantations as such but to determine the variation in factor patterns between season, canopies and soil depth.

7.2.1. Materials and Methods

The data on soil parameters generated from teak plantations and adjacent natural forest and eucalypt plantations and adjacent natural forest were subjected to factor analysis separately for reducing the dimension of the problem. The factor analysis was carried out using SPSS software package (Norusis, 1988). The analysis was done on a correlation matrix. Principal component analysis was used as a method of factor extraction (Harman, 1976) and all factors with eigen values greater than one were considered. In the factor extraction phase, the number of common factors needed to adequately describe the data were determined.

Kaiser Meyer Olkin (KMO) measure of sampling adequacy was calculated. The KMO statistics (Kaiser, 1970) was calculated for individual and multiple variables and represents the ratio of squared correlation between variables to the squared partial correlation between variables. The KMO statistics varies between zero and one. The value of zero indicates that sum of partial correlation is large relative to the sum of correlations. indicating diffusion in the pattern of correlation. A value close to one indicated that pattern of correlations are relatively compact and so factor analysis should yield distinct and reliable factors (Field, 2000). In our case, the KMO value was 0.677 for factor analysis of soils of natural forest and teak plantations and 0.790 for natural forest and plantations of eucalypt. According to Kaiser (1974) the values were good.

Bartlett's measure of sphericity was significant (χ^2 = 1038.912and 855.212). Bartlett's measure tests the null hypothesis that the original correlation matrix is an identity matrix. A significant result tells us that there are some relationship between variables we hope to include in our study. Hence factor analysis is appropriate for the present data set. The values of KMO and Bartlett's Test for teak plantations and adjacent natural forest and eucalypt plantations and adjacent natural forest are given in Appendix 79. Factor scores for each factor were computed for individual soil samples. Analysis of variance on factor scores for each of the factors was carried out to examine how the factor pattern varied between natural forest and plantations.

7.2.2. Results and Discussions

7.2. 2.1.Teak plantations and natural forest

Factor analysis identified five factors, which together accounted for 67.1 per cent of total variation in soil properties. The proportion of variance explained by the common factors is called the communalities. The five factor model explained ≥89 per cent of variance in bulk density, ≥ 82 per cent of variance in sand, ≥82 per cent of variance in organic carbon, ≥78 per cent of variance in clay, ≥75 per cent of variance in water holding capacity, ≥74 per cent of variance in exchangeable potassium, ≥73 per cent of variance in exchangeable copper, ≥71 per cent of variance in exchangeable iron, ≥69 per cent of variance in exchangeable manganese, ≥69 per cent of variance in pore space, ≥65 per cent of variance in total nitrogen, ≥62 per cent of variance in exchangeable calcium, ≥61

Table.11. Factor loadings and communalities of soil variables in teak plantations and natural forest

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Communalities
G	-0.419	0.189	-0.267	0.483	0.289	0.599
S	0.05335	0.807	-0.163	-0.344	-0.155	0.824
Cly	-0.221	-0.757	0.320	0.246	-0.03460	0.781
BD	-0.833	0.171	0.354	-0.219	-0.03887	0.897
PS	0.711	-0.07464	-0.300	0.268	0.135	0.691
WHC	0.635	-0.456	-0.156	0.291	-0.187	0.756
pH	-0.494	0.138	0.251	0.03473	-0.310	0.423
Ex. Base	0.184	0.419	-0.213	-0.05512	0.477	0.486
Ex. Na	0.298	0.559	-0.364	0.179	-0.03842	0.567
Ex. K	0.365	-0.490	-0.009784	-0.484	0.363	0.740
Ex. Ca	0.543	0.373	0.353	0.06111	0.243	0.621
Ex. Mg	0.591	0.07633	0.101	0.428	0.255	0.614
Av. P	0.328	0.189	0.489	-0.407	0.261	0.616
OC	0.773	0.09623	0.274	-0.173	-0.335	0.823
Total. N	0.503	0.325	0.461	-0.04531	-0.287	0.656
Ex. Fe	-0.315	-0.09827	0.538	-0.02716	0.562	0.715
Ex. Cu	-0.472	0.543	0.08179	0.446	0.07971	0.730
Ex. Zn	0.245	0.127	0.638	0.156	0.04425	0.509
Ex. Mn	0.07171	0.06616	0.651	0.488	-.146	0.693
Percentage variation explained	22.731	15.123	12.995	9.130	7.117	

Extraction Method: Principal Component Analysis per cent of variance in exchangeable magnesium, 61 per cent of variance in available phosphorus, ≥59 per cent of variance in gravel content, ≥56 per cent of variance in exchangeable sodium, 42 per cent of variance in pH, ≥50 per cent of variance in exchangeable zinc and ≥48 per cent of variance in exchangeable bases (Table.11).

Factor loadings are a gauge of the substantive importance of a given variable to a given factor. The first factor accounted for 22.7 per cent of the total variation in the soil properties and had a high positive loading on organic carbon, water holding capacity, pore space, exchangeable calcium, magnesium and total nitrogen and a high negative loading on bulk density. As this factor measures fertility and compaction of soil, it is termed as fertility and compaction factor.

Analysis of variance on factor scores is given in Appendices 80-89. The mean factor scores for fertility and compaction were significantly different between natural forest and teak plantations in the 0-20cm, 20-40cm and 40-60cm depths in younger teak plantations and in both the older teak plantations, the difference is significant in 0-20cm depth. The factor scores for fertility and compaction factor in plantations were lower than that of natural forest. As soils of teak plantation were more compacted and had lower organic matter than soils of natural forest, the fertility and compaction score was correspondingly lower. The difference was non-significant between the oldest age class teak plantation and natural forest in the 20-40 and 40-60cm depth. Among teak plantations, fertility and compaction factor showed no significant difference.

The second factor accounted for 15.12 per cent of total variation in soil properties and showed a high positive loading on sand and a high negative loading on clay. As this factor reflects the texture of soil, it is named as texture factor. The mean factor score for texture factor in plantations are higher than that of natural forest. This is in accordance with the lower amount of finer fractions in plantation soils. The mean scores of texture factor in natural forest and older age class plantations differed significantly from each other in all the three depths. On the other hand, the mean scores of 21-30Y age class teak plantations in 0-20cm depth and 31-40Y age class plantations at 20-40 and 40-60cm depth, did not differ significantly from natural forest soils of corresponding depth.

The third factor accounted for 12.995 per cent of total variation in soil properties and showed a high positive loading on manganese, zinc and iron. As these factors reflect the micronutrient status of plantations soils, it is called as micronutrient factor. The mean scores of micronutrient factor, in the 0-20 and 20-40cm depths, were significantly higher than natural forest in 31-40Y age class plantations. On the contrary, in older teak plantations, the score was lower than that of natural forest and decreased with age. The difference was significant in 0-20cm depth and 20-40cm depth in younger teak plantations.

The fourth factor accounted for 9.13 per cent of total variation in soil properties and showed a high negative loading on exchangeable potassium and positive loading on gravel. Hence, this factor is called as potassium factor. Potassium factor did not differ significantly between soils of natural forest and younger teak plantations. On the other hand, in the oldest age class plantation, the mean score of potassium factor was significantly higher than that of natural forest in the 20-40 and 40-60cm depth. This may be because of the decrease in exchangeable potassium values with plantation age.

The fifth factor accounted for 7.117 per cent of total variation in soil properties and showed a high positive loading on exchangeable bases and exchangeable iron. This factor is named exchangeable bases and iron factor. The mean scores of exchangeable bases in the younger age class plantations were higher than that of natural forest. A significant difference from natural forest was observed in 21-30Y age class plantation in the 20-40cm depth and in 31-40Y age class plantation in 20-40 and 40-60cm depths. In older age class plantations, the mean factor score was lower than that of natural forest and generally decreased with age. The difference from natural forest was significant at all depths in the oldest plantation under study. In 41-50Y age class plantation, the difference was significant in the 20-40 and 40-60cm depth.

7.2. 2. 2. Eucalypt plantations and natural forest

Factor analysis identified four factors, which together accounted for 71.211 per cent of total variation in soil properties. The four factor model explained for ≥93 per cent of variance in clay, ≥ 92 per cent of variance in sand, ≥88 per cent of variance in organic carbon, >85 per cent of variance in bulk density, ≥81 per cent of variance in exchangeable calcium, ≥79 per cent of variance in particle density, >80 per cent of variance in total nitrogen, ≥76 per cent of variance in exchangeable magnesium, ≥75 per cent of variance in pH, ≥67 per cent of variance in exchangeable potassium, ≥65 per cent of variance in exchangeable sodium, ≥65 per cent of variance in exchangeable zinc, ≥63 per cent of variance in gravel content, ≥62 per cent of variance in exchangeable bases, ≥62 per cent of variance in exchangeable copper, 61 per cent of variance in available phosphorus, ≥59 per cent of variance in exchangeable manganese, ≥48 per cent of variance in exchangeable iron, and ≥43 per cent of variance in water holding capacity (Table 12).

The first factor accounted for 37.68 per cent of total variation in soil properties and had a high positive loading on organic carbon, total nitrogen, exchangeable calcium, pH, exchangeable bases, pore space, exchangeable manganese, water holding capacity and exchangeable magnesium. The factor also has a high negative loading on bulk density and exchangeable iron. As this factor measures the fertility status, nutrient capital and compaction of soil, it is named as fertility, nutrient capital and compaction factor. The mean factor score for the plantations significantly lower than natural forest in the 0-20 and 20-40cm depth. In the 40-60cm depth, the difference between the mean factor score of natural forest and third rotation plantations was significant. It was also observed that the mean factor score lowered significantly with rotation. This is an indication of overall decline in nutrient capital and fertility of soils in plantations.

The second factor accounted for 14.571 per cent of total variation in soil properties and had a high positive loading on sand and a high negative loading on clay. As this factor assesses the texture of soil, it is called the texture factor. The mean factor scores for plantations were higher than that of natural forest and is a reflection of the higher coarse fragments in soils of plantation compared to that of natural forest. The difference was significant in all the three depths in third rotation replanted plantation.

Table 12. Factor loadings and communalities of soil variables in eucalypt plantations and natural forest

	Factor 1	Factor 2	Factor 3	Factor 4	Communalities
G	-0.648	-0.232	0.375	-0.161	0.639
S	-0.06512	0.770	0.553	-0.138	0.923
Cly	0.177	-0.756	-0.522	0.234	0.930
BD	-0.707	-0.251	0.411	0.343	0.850
PS	0.801	0.271	-0.131	-0.259	0.799
WHC	0.532	-0.01526	-0.394	0.008964	0.439
pH	0.773	-0.395	-0.01207	-0.03837	0.755
Ex. Base	0.773	0.109	0.125	0.04056	0.627
Ex. Na	-0.536	0.304	-0.509	0.112	0.652
Ex. K	0.455	0.230	-0.181	0.618	0.675
Ex. Ca	0.856	-0.191	-0.203	0.01297	0.811
Ex. Mg	0.493	-0.114	0.678	0.210	0.760
Av. P	-0.273	0.675	-0.291	-0.02056	0.616
OC	0.881	0.268	-0.159	-0.118	0.888
Total. N	0.897	0.03479	-0.01162	-0.03621	0.807
Ex. Fe	-0.621	-0.139	-0.273	0.06718	0.484
Ex. Cu	0.118	-0.621	0.441	-0.179	0.626
Ex. Zn	0.350	0.328	0.389	0.524	0.656
Ex. Mn	0.661	-0.09626	0.381	-0.05505	0.594
Percentage variation explained	37.680	14.571	13.39	5.5	

Extraction Method: Principal Component Analysis.

The third factor accounted for 13.39 per cent of total variation in soil properties and had a high positive loading on exchangeable magnesium and is named as magnesium factor. In both the coppiced plantations, the difference was significant in the 0-20cm depth. The fourth factor accounted for 5.5 per cent of total variation in soil properties and had a high positive loading on exchangeable potassium and zinc. Hence this factor is named potassium and zinc factor. The mean factor score does not differ significantly between natural forest and plantations in the 0-20, 20-40 and 40-60cm depth.

7.2.2.3. Comparative evaluation

When the data were subjected to factor analysis, a five factor model explained the variation in teak plantations while a four factor model explained the variation in eucalypt plantations (Table 13). In teak plantations, the fertility and compaction factor accounted for the maximum variation in soil properties, *viz.*, 22.7 per cent. On the other hand, in eucalypt plantations, the maximum variation in soil properties (37.6 per cent) was explained by fertility, nutrient capital and compaction factor. In teak plantations, the fifth factor loaded positively on exchangeable bases and exchangeable iron and accounted for seven per cent variation in soil properties. In contrast, exchangeable bases in eucalypt plantations loaded highly on the first factor. It was also observed that although pH loaded on the first factor in both plantations, the factor loading in eucalypt was higher than that of teak. The same was true for exchangeable calcium and total nitrogen. This is an indication that variation from natural forest was more extensive under eucalypt soils than in teak. The texture factor accounted for comparable variations in both plantations of teak and eucalypt, *viz.*, 15.1 and 14.5 per cent, respectively.

In a study to identify the factor pattern in different vegetation types *viz.*, evergreen, semi evergreen, moist deciduous forest and plantations of teak, eucalypt and rubber, Rugmini and Balagopalan (2006) obtained a three-factor model. The factors obtained were aggrading factor, texture and acidity factor. The first and second factors in this five and

Table 13. Comparison of factor model

Teak and natural forest	Percentage variation explained	Eucalypt and natural forest	Percentage variation explained
1) Fertility and compaction • + organic carbon • + pore space • + water holding capacity • + ex. calcium • + ex. magnesium • + total nitrogen • - bulk density	22.7	1) Fertility, nutrient capital and compaction • + organic carbon • + total nitrogen • + ex. calcium • + pH • + ex. bases • + pore space • + ex. manganese • + water holding capacity • + ex. magnesium • - bulk density • - ex. iron	37.68
2) Texture • + clay • - clay	15.12	2) Texture • + clay • - clay	14.571
3)Micronutrient factor • + ex. manganese • + ex. zinc • + ex. iron	12.995	3) Magnesium • + ex. magnesium	13.39
4) Potassium • - potassium • + gravel	9.13	4) Potassium and zinc • + potassium • + zinc	5.5
5) Exchangeable bases and Iron • + ex. bases • + iron	7.117		

four factor models were similar. As in the present study, the dominant factor *viz.*, aggrading factor loaded highly on organic carbon, total nitrogen and bulk density.

7.3. Soil fertility Index

The fertility status of soils under natural forest and plantations can be measured in terms of the concentration of exchangeable nutrients and water holding capacity. By relating the values of these properties in plantation soils to that of natural forest, the extent of degradation, if any, in soils of plantations can be assessed. Soil fertility index is an extremely valuable tool to do this effectively. Thus, instead of looking at each property in isolation, it will be possible to assess the fertility status of soils as a whole. Moreover, it also enables to study the variation in fertility of plantation soils with time.

7.3.1. Materials and Methods

Five variables are used in calculating the index: Organic carbon concentration, total nitrogen concentration, water holding capacity, exchangeable bases and concentration of available phosphorus. In the first step, the properties in natural forest are assigned a score of hundred. The score for each of these properties in plantations were then calculated by expressing the mean value of these properties as a per cent of that in the adjacent natural forest. Analysis of variance was performed on soil variables and properties which differed significantly from natural forest at one per cent level were noted. In the next step, for those properties of plantations which did not differ significantly between natural forest and plantations, the calculated score was replaced by the score for natural forest *viz.*, hundred. The fertility index was then calculated by computing the average of these scores (modification of Aweto fertility index, 1981).

The study of soil properties in plantations and natural forest led to the conclusion that the variation in soil properties was maximum in the 0-20cm depth. This was because soils in the 0-20cm depth was most affected by plantation activities and exposed to the vagaries of nature. Hence, to calculate the fertility index, only soil properties of this depth were considered.

7.3.2. Results and Discussion

7.3.2.1. Teak

The fertility index for 21-30Y, 31-40Y, 41-50Y and >50Y teak plantations were 86.5, 83.1, 94.2 and 93.1, respectively. The fertility of teak plantations first decreased and then increased with age of the plantations. For the establishment of plantations, the natural forest was clearfelled and slash burned. In the beginning, the soils were exposed to the environment and erosion was wide spread. This resulted in the loss of nutrient rich top soil. Nutrients were also lost from soil by leaching. Furthermore, exposure of soil to sunlight leads to faster decomposition and eventual loss of organic matter. All these factors contributed to the lowered fertility in younger teak plantations.

As the plantation grows, it provides a measure of cover to the soil. Furthermore, addition of litter to soil and its decomposition increased soil organic matter and nutrient status of soils. However, the first twenty five year after establishment of a teak plantation are periods of intensive soil disturbance. Mechanical and silvicultural thinning was carried out during this period, resulting in decreased soil cover and periodic soil disturbance. The net result is progressive loss of soil fertility. The mechanical and silvicultural thinning ends by 25 years. Now the soil gets a chance to recuperate. It is probable that at this stage, the rate of nutrient return to the soil through the fall and break down of litter is greater than its loss from soil. Thus, soil fertility increases with age of the plantation.

7.3.2.2. Eucalypt

The fertility index for second rotation, third rotation coppiced and third rotation replanted plantations were 78.6, 68.1 and 74.3, respectively. The fertility status in eucalypt plantations was lower than natural forest and found to decrease with rotation. The disturbance to soil during clear felling and the loss of soil cover in the initial years of plantation establishment often leads to enhanced erosion and loss of nutrient rich top soil.

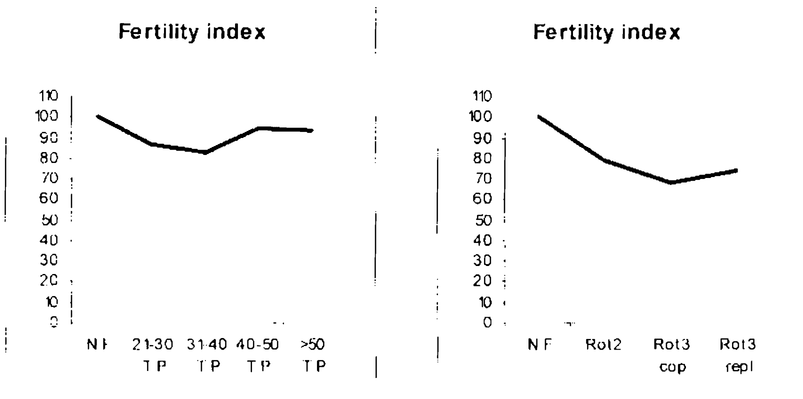


Fig. 42 Fertility index in teak and eucalypt plantations

Moreover, shorter rotation results in more frequent exposure to the atmosphere and disruption to the flow of nutrients to the soil through litter. Nutrients are also lost from the soil by harvesting. All this contribute to the lower fertility status of eucalypt plantations and a continuous decline in fertility with rotation.

Among third rotation plantations, replanted plantations had higher fertility index than coppiced one. Replanted plantations were fertilized in the initial year of plantation establishment. This enhanced nutrient capital of the soil. It might have also led to enhanced growth and higher litter return. Organic carbon content in replanted plantation soils was thus higher than coppiced ones. These translate into higher soil fertility in replanted plantations than coppiced one.

7.3.2.3. Comparative evaluation

When fertility index values for teak and eucalypt plantations were compared, it could be concluded that loss of fertility was greater in eucalypt plantations than in teak plantations. It was also observed that, in plantations of teak, fertility initially decreased and then increased with age of the plantation. An increase in soil fertility of teak plantations was apparent only after 40 years of its establishment. After 40years, an increase in soil fertility was noticed. At the end of rotation, fertility index of teak plantations were lower than natural forest by seven points.

In plantations of eucalypt, fertility decreased with rotation. The fertility index of second rotation plantation was lower than natural forest by 21 points while the fertility index of third rotation plantation (coppiced and replanted) were lower than natural forest by 32 and 26 points, respectively. The soil fertility of third rotation plantations was lower than that of second rotation plantation by ten and four points respectively.

From the soil fertility index values, it is apparent that, under the current management practices, short rotation eucalypt plantations degrade soils to a greater extend than long rotation teak plantations. Unless ameliorative measures are taken to increase the soil fertility, eucalypt plantations may be unsustainable over long periods. Furthermore, any decision to decrease the rotation period of teak plantations should also take into account the pattern of soil fertility variation within a rotation.

Chapter 8

General Discussion

Forest plantations are an increasingly important resource world wide especially Kerala. Teak, a high value long rotation crop, is a major plantation crop in the State. At present, it is managed in a 60Y rotation, though questions about the advisability of retaining this long rotation period are being raised. The discussion about rotation age is mostly confined to the economic aspects and not much thought spared to its sustainability. Any discussion on this aspect is also hampered by lack of relevant data. Studies that compare one or two plantations of teak or eucalypt with adjacent natural forest, though useful to understand the soil status in plantations, throw no light on the changes in soil properties with time. It also does not provide any information about possible soil recuperation. Hence, the effect of shorter rotation on soils in teak plantations cannot now be adequately predicted.

In this context, this study which traces the variation in physical and chemical properties and nutrient status of teak soils with age of plantations, till the end of a rotation period is highly pertinent. The data generated will be more useful if accompanied by information on soil changes following a short rotation plantation crop. Eucalypt, a major short rotation crop in Kerala, would bring out the possible impact of short rotation.

The importance of micronutrient to soil productivity is now widely recognized. However information about micronutrient status of plantations in India is woefully inadequate. This study not only generates pioneering information about micronutrient status of plantation soils but also throws light on the variation in micronutrient status with age in teak plantations and with rotation in eucalypt plantations.

It was observed that soils of plantations had higher gravel contents and bulk density and lower pore space and water holding capacity values than natural forest. Although this trend was observed in all the three depths, the difference was most pronounced in the surface *viz.*, 0-20cm depth which is the layer most affected by plantation activities. In natural forest, gravel contents and bulk density increased and water holding capacity and pore space values decreased with depth. Such a clear trend was not noticed in plantations which is an indication of their disturbed status.

As the plantations grow old, a general trend of decline in relative gravel per cent with age was observed. This showed that in older teak plantations, soils started recuperating. This decline in gravel contents over time could not be observed in eucalypt plantations where a significant increase with rotation was noticed. Bulk density values also increased with age in younger teak plantations. In the older plantations, the values were lower than those in younger plantations. This could be due to the relationship between bulk density and organic carbon, the latter being higher in older teak plantations. The absence of further disturbance in older teak plantations, by way of thinning operations, could also contribute to the lower compactness in older plantations. Although, soils of both teak and eucalypt plantations were more compacted than natural forest, greater compaction was observed in plantations of eucalypt than teak. Significantly higher bulk density values in teak plantations compared to natural forest was observed in 0-20cm depth. On the other hand, in eucalypt soils, a significant increase was observed in all the three depths.

Water holding capacity values of younger teak plantations differed from natural forest in both 0-20 and 0-60cm depth. In contrast, a significant difference was confined to 0-20cm depth in older plantations. On the other hand, plantations of eucalypt had significantly lower water holding capacity than natural forest in 0-20, 20-40 and 40-60cm depth. Water holding capacity decreased with depth in natural forest though the finer separates increased down the profile. This was due to the influence of organic carbon on water holding capacity. As the water holding capacity of soils is controlled to a greater extent by organic matter, the more the organic matter in soils, higher the water holding capacity (Ghosh and Bhardwaj, 2002) It was also observed that in deeper layers, the organic matter was found to decrease due to low incorporation of litter when compared to the surface layer. This decrease in organic carbon with depth also explains for the decrease of water holding capacity.

A significant decline in pore space values was confined to the 0-20cm depth in younger teak plantations. In eucalypt plantations, significant difference was noted in the 0-60cm depth. As pore space is interrelated with compactness (Bulk density) which in turn is influenced by soil organic matter (Ghosh and Bhardwaj, 2002; Das and Agrawal, 2002), the more the organic matter, higher the pore space. As the soil organic matter in younger teak plantations was relatively lower than that of natural forest, similar trend was also observed in pore space. The organic carbon content in older teak plantations was comparatively higher than that in younger teak plantations and hence it could be expected that the pore space would be higher in older plantations and close to that in natural forest. This could be the reason for the difference to be significant only in younger teak plantations.

Another aspect with respect to teak is that it is a long rotation crop while eucalypt is a short rotation one. Due to the short rotation nature of eucalypt, the soils in the plantations are more frequently disturbed compared to the long rotation teak plantation. This could lead to intermittent loss of organic matter from eucalypt soil when compared to teak. This intermittent loss of organic matter from eucalypt plantations might have lead to low incorporation of organic matter into deeper layers, resulting in a greater decline in organic carbon with depth. The greater decline in organic matter with depth in eucalypt plantations resulted in lower pore space in deeper layers.

The very process of plantation establishment, which involves clearfelling of natural forest, exposes the soil to disruptive forces of nature like wind, rain and sunlight. The loss of soil cover (accumulated litter), canopy cover, undergrowth, coupled with disturbances at the time of burning the slash and the site preparation for establishment of plantations might have caused accelerated soil erosion and increased compaction. During erosion, the top soil is most susceptible to loss. In some cases, it was noticed that the subsurface layer got exposed to the surface. In an alternative scenario, it was also seen that gravel was left behind and fine particles lost from the surface. Both these processes led to higher gravel contents in plantation soils and coarsening of texture.

It was also observed that highest relative mean values of bulk density and gravel and lowest relative mean values of pore space and water holding capacity was found in 31-40Y age class plantations. Major thinning operations in teak plantations are usually over by 30Y after which, there is no disturbance to the plantations and site. Soil now has a chance to recuperate. Due to longer rotation period of teak plantations, as the plantations grow old, accumulation of the litter on the ground, partial canopy closure and the growth of under-storey in plantations lead to decreased rate of erosion. This translates into a general trend of decline in relative gravel per cent with age. Increased water holding capacity and pore space and decreased bulk density values in older plantations are indications of soil recuperation. Such an improvement in soil conditions was not observed in eucalypt plantations. This is because of the short rotation nature of eucalypt.

When soils in natural forest, teak and eucalypt were compared, it was observed that plantation activities changed soil pH. Soils in teak showed an increase in soil pH values while those in eucalypt showed a decreasing trend. This could be due to the fact that deciduous trees like teak tend to add more bases to the soil (Balagopalan and Jose 1982b), while this is not applicable to eucalypt. In plantations of eucalypt, the soil acidity is predominantly influenced by the loss of bases, either by leaching or erosion. Soil pH values decreased over rotations which was predominant in the lowest depth. The same above factors might have influenced the exchangeable bases status in plantation soils. In teak, the difference from natural forest was not pronounced while the decline in eucalypt, especially in third rotation plantations, was significant.

The effect of eucalypt plantations on exchangeable sodium was more pronounced than that in teak. Sodium contents in soils of natural forest and younger age class plantations, in the 0-60cm depth, were very close. In older teak plantations, the values were slightly higher than those of natural forest and the difference, though small, was significant in oldest teak plantation. Conversely, in eucalypt plantations, the values were very close to the natural forest and second rotation plantations while in third rotation plantations, the values were significantly higher. It was also observed that among soils in teak and eucalypt plantations for similar periods, *viz.*, 30-40 years, the increase of exchangeable sodium content in eucalypt plantations was much greater than that of teak.

Soils in teak and eucalypt plantations were not largely affected by plantation activities with respect to exchangeable potassium. A small but significant decrease from natural forest was confined to older teak plantations. Plantations of teak and eucalypts differed in their effect on soil exchangeable calcium. A significant decline in exchangeable calcium was observed in eucalypt plantations in the 0-60cm depth, which had lost almost 50 per cent of exchangeable calcium. On the other hand, in teak, no such difference was observed.

Available phosphorus showed contrasting pattern of variation in soils of teak and eucalypt plantations. Soils in the 0-60cm depth of younger teak plantations and natural forest did not differ significantly from each other in phosphorus values, though older teak plantations showed a slight but significant decline. On the other hand, soils in eucalypt plantations demonstrated an increase in phosphorus availability with rotation.

Soils in teak and eucalypt plantations were poorer in organic carbon than those in the natural forest and the difference was most pronounced in the upper layer. In teak plantations, soil organic carbon was found to decrease initially and then increase with age, with the soils of oldest plantation approaching natural forest. In eucalypt plantations, such a pattern of variation was not observed. Organic carbon in soils decreased with rotations, although in replanted plantations, an increase in organic carbon content was observed. Soils in plantations were also lower in total nitrogen contents than natural forest and mirrored the pattern of variation in organic carbon. However, the difference was significant only in eucalypt plantations. A decrease in total nitrogen with rotations was also observed and the decrease was significant in the 0-20 and 20-40cm depths.

The higher organic matter in natural forest is predominantly due to diversity of vegetation cover (Lundgren, 1978) and the resultant litter diversity which supports a variety of microorganisms leading to faster mineralization. Moreover, lower erosion in natural forest results in conversion of organic matter (Maro *et al.*, 1993). The teak plantations were established by clearfelling and burning of slash. This results in wide spread erosion and loss of top soil along with the organic carbon in it. However, as the plantations grow, addition of litter to soil and its decomposition increases soil organic matter. Also, as teak grows, it provides a measure of cover to the soil. The plantations of teak are subjected to mechanical and silvicultural thinning, which disturbs the soil and temporarily decreases the soil cover. It is also detrimental to the development of undergrowth. Litter production at this stage appears to be inadequate to balance for the loss of organic carbon. The net result is progressive loss of soil organic carbon. The mechanical and silvicultural thinning ends by around 30 years in Kerala condition and the soil starts to recuperate after this period. It is probable that at this stage, the rate of nutrient return to the soil through the fall and break down of litter is greater than its loss from soil. Thus, there is scope for an increase in soil organic carbon and in the older age class plantations, the values were higher.

Eucalypt is a short rotation crop and hence the flow of carbon and nutrients to soil is disrupted more frequently. Also, as the time between each successive rotation is short, the chances for soil recuperation are inadequate. Thus, organic carbon in plantations of eucalypt were found to decrease with rotation. Among third rotation plantations, higher organic carbon was observed in replanted plantations than coppiced ones. This could be due to the application of fertilizers in replanted plantations. This fertilizer application could have increased the growth of eucalypt that would translate into higher litter fall and eventually higher organic matter in the soils under it. Increase in soil organic carbon as a result of fertilizer application was reported by Hussein (1995) and Johnson (1992). On the other hand, in coppiced plantation, where fertilizer was not applied, organic carbon was found to be lower.

When plantations under teak and eucalypts for similar period of time (30-40Y period) were compared, it was observed that the loss from eucalypt was greater than in teak. Soils under teak for more than 40 years showed a dramatic increase in organic carbon content. From the data available, such an increasing trend in eucalypt plantations cannot be expected.

Changes in organic carbon status also affected various other soil properties. Organic carbon was significantly and negatively correlated with bulk density, particle density, available phosphorus and positively with water holding capacity, exchangeable bases, exchangeable potassium, calcium and total nitrogen. The lowest relative mean values for organic carbon, pore space, water holding capacity, total nitrogen and highest relative mean values for bulk density, particle density and available phosphorus were noted in 31-40Y age class plantations. Among eucalypt, the lowest relative mean values for organic carbon, exchangeable potassium, exchangeable calcium and total nitrogen were observed in third rotation coppiced plantations.

Increase in gravel content and bulk density values and decrease in pore space, water holding capacity values, exchangeable potassium, organic carbon and total nitrogen in plantations soils was reported by Balagopalan (1987, 1995a, b), Bargali *et al.* (1993), Balagopalan and Jose (1983, 1986, 1993, 1997) and Amponsah and Meyer (2000). Close exchangeable bases, extractable calcium and available phosphorus values in soils of natural forest and an adjacent teak plantation was recorded by Balagopalan (1995a, b). These findings are in agreement with our study, though, they cannot be compared in toto with the present study. This is because the above mentioned studies compared one or two plantations with adjacent natural forest and provided no information about trends in soil properties or possible soil recuperation.

Balagopalan in two separate studies (1987, 1995b) compared bulk density, texture, pH, exchangeable bases, available phosphorus, potassium, total nitrogen and organic carbon in successive rotation eucalypt plantations and adjacent natural forest. However, no study in third rotation area has yet been reported. The study by Balagopalan (1987, 1995b) found that total nitrogen and organic carbon decreased with rotation.

Studies on micronutrients in forest soils are few in number. Studies on plantations of teak and eucalypt are still fewer. A study by Karia and Kiran (2004) on micronutrients in forest soils of Chhotaudepur exist, but, it does not cover the micronutrient status of teak plantations. Micronutrient availability in different age eucalypt plantations was carried out by Sangha and Jalota (2005). However, no studies on variation in micronutrient availability with age in teak plantations or with rotation in eucalypt plantations were reported previously. Similarly, studies that compare soils of teak and eucalypt plantations with natural forest have not been carried out.

Study of micronutrients in plantation soils led to the conclusion that the values for exchangeable iron in plantations of eucalypt were significantly higher than that of natural forest and the values increased with rotation. However, in teak plantations, an initial increase was followed by a decrease in the older plantations in the 0-60cm depth. The difference was significant in younger teak plantations and non-significant in older teak plantations. Exchangeable iron was found to be significantly and negatively correlated with organic carbon, though the magnitude of correlation was low and the change in exchangeable iron status of plantation soils may be mediated through soil organic carbon.

When exchangeable copper status in plantation soils was studied, contrasting pattern of variations from natural forest was observed in teak and eucalypt plantations. Soils in teak plantations were richer in exchangeable copper than natural forest whereas those of eucalypt were poorer. The difference from natural forest was significant in both plantations in the 0-60cm depth. Soils in teak and eucalypt plantations and natural forest did not differ significantly from each other with respect to exchangeable zinc values. Availability of manganese in plantation soils decreased with rotation. The difference from natural forest values was significant in the third rotation in the 0-60cm depth. In plantations of teak, such a clear pattern or significant difference was not seen.

Soils in natural forest and plantations of teak did not differ significantly in manganese availability. On the other hand, availability of manganese in eucalypt soils decreased with rotation and the difference was significant in third rotation plantations. This could be due to absorption of manganese from soil by eucalypts. Baber *et al.* (2006) had observed that manganese in surface soil decreased as distance increased from the tree in plantations of eucalypt. This also supports the above supposition. Lower availability of manganese in older eucalypt plantations was also observed by Sangha and Jalota (2005).

The micronutrient cations (copper, zinc, manganese and iron) have rather complex chemical relationships, controlling their availability in soils. Overall, the relative availabilities are controlled by the equilibria that exist between the soil solution, the soil organic matter, the cation exchange sites, and insoluble compounds.

In the case of exchangeable iron, a significant and negative correlation was obtained with organic carbon. Among teak plantations, lowest relative mean organic carbon values corroborate the highest relative availability of iron in 31-40Y age class plantation soils.

Among third rotation plantations, higher organic carbon and lower exchangeable iron was observed in replanted plantations when compared to coppiced one. The soil organic matter acts as a "storehouse" for many of these elements. As the organic matter decomposes, the nutrients are released and thus the organic matter tends to act as a continuous nutrient supplier. Soil organic matter also influences micronutrient availability through chelation. Chelation is the combination of a metallic ion with an organic molecule with varying degrees of bonding. This combination of the two in a claw-like manner can either increase or decrease the availability of the micronutrient. In the present study, it is seen that soil organic matter is the most predominant factor that affected the exchangeable iron contents and had a negative relationship between these two.

With regard to copper, it was observed that there was positive correlation with soil pH. This is quite expected as soil solution controls the availability of exchangeable copper in soils. In the present study, the soil pH varied from 4.5 to 6.5 i.e. from strongly acidic to close to neutral range and hence availability of copper increased with soil pH. In the case of zinc, no significant difference was observed between soils of natural forest and plantations. In other words, zinc status was not significantly affected by plantation activities. The availability of zinc is influenced by both pH and OC content. Younger teak plantations and natural forest had soils with pH values very close and exchangeable zinc also followed the same pattern. In the oldest teak plantation, a slight increase in pH was observed, which resulted in still lower zinc content. In the case of eucalypt, it was noted that the zinc content increased and then decreased followed by a gradual increase in replanted one. Actually, zinc content should increase with lowering of pH. This phenomenon was observed in second coppiced plantation. In the third coppiced plantation, the value was lower due to its positive relation with organic carbon.

Proximate constituent varied between soils of natural forest and plantations. Fats and waxes, free sugar, hemicellulose, cellulose, protein and lignin-humus in soils of monoculture plantations were significantly lower than that of natural forest. As the proximate constituents are derived from organic matter, the trend observed with respect to organic carbon is followed for the proximate constituents in toto. However, significantly higher resin contents was observed in eucalypt plantations compared to teak and natural forest. This can be attributed to the resinous nature of eucalypt leaf litter. These observations are in concurrence with the findings of Singhal (1986), Singh and Singhal (1974) and Balagopalan (1991).

In general, contribution of lignin to proximate constituents was found to be the highest, irrespective of the vegetation type. This is because lignin is broken down only very slowly in soil. On the other hand, the least contribution was from free sugars. The reason may lie in the easy solubility of free sugars that may lead to their rapid loss from soil. Also, free sugars are the most easily available food for the microorganisms. Among the proximate constituents, hemicellulose and cellulose, the rate of decomposition of hemicellulose was initially greater and subsequently slower than that of cellulose, resulting in higher content of hemicellulose in all the vegetation types.

Factor analysis was carried out to reduce the number of variables that explains the difference or similarities between soils under plantations and natural forest. Factor analysis on soils of natural forest and teak plantation led to a five factor model which accounted for 67.1 per cent of total variation in soil properties. These were fertility and compaction factor, texture factor, micronutrient factor, potassium factor and exchangeable bases factor. The difference in soil properties between natural forest and eucalypt could be explained by a four-factor model that accounted for 71.2 per cent of variation. The factors were fertility, nutrient capital and compaction factor, texture factor, magnesium factor and potassium and zinc factor. In teak plantations, the fertility and compaction factor accounted for the maximum variation in soil properties, *viz.*, 22.7 per cent. On the other hand, in eucalypt plantations, the maximum variation in soil properties (37.68 per cent) was explained by fertility, nutrient capital and compaction factor.

Although pH loaded on the first factor in both plantations, the factor loading in eucalypt was higher than that of teak. The same was true for exchangeable calcium and total nitrogen. This is an indication that variation from natural forest was more extensive under eucalypt soils than in teak. The texture factor accounted for comparable variations in both plantations of teak and eucalypt, *viz.*, 15.12 and 14. 57 per cent, respectively.

Rugmini and Balagopalan (2006) obtained a three-factor model to differentiate between soils in evergreen, semi evergreen, moist deciduous forest and plantations of teak, eucalypt and rubber. The factors obtained were aggrading factor, texture and acidity factor. The first and second factors obtained in the present study were similar. As in the present study, the dominant factor *viz.*, aggrading factor loaded highly on organic carbon, total nitrogen and bulk density.

To obtain a clear picture regarding the extent of degradation or recovery of soil consequent to plantation activity, soil fertility index was calculated. When fertility index values for teak and eucalypt plantations were compared, it could be concluded that loss of fertility was greater in eucalypt plantations than in teak. In plantations of eucalypt, fertility decreased with rotation. It was also observed that, in plantations of teak, fertility initially decreased and then increased with age of the plantation. An increase in soil fertility in teak plantations was apparent only after 40 years of its establishment.

From the foregoing, it is proved that the soil health in teak plantations of varying age classes and eucalypt plantations of different rotations were lower than those in the natural forest. Over time, better recuperation takes place in teak plantations when compared to eucalypt where continuous degradation over rotation takes place. With in a rotation period, in teak plantations, recuperation starts around 40Y onwards after establishment. Weather this phenomenon prevails or not in successive rotations of teak and in other agro ecological zones needs to be studied in detail.

Chapter 9

Summary and Conclusions

Plantations are a significant component in terms of area and revenue of Kerala Forest Department. Currently 50 per cent of area under plantations in the State is under teak and 25 per cent is under eucalypt accounting for 75 per cent of plantation area. From the very beginning of plantation forestry, fear of soil deterioration in monoculture plantations was expressed. Numerous studies in plantation soils, especially in teak and eucalypt are available. However, a large number of these studies were attempts to correlate soil properties with decline in productivity of plantations during rotation cycle while very few studies compared soils in plantations with barren lands to assess the effect of afforestation.

Reports indicate that site deterioration between and within rotation in teak posses a threat to potential yield and sustainable management. In India, questions about the advisability of retaining the 60 year rotation are being raised. However, the effect of shorter rotation on soils in teak plantations cannot now be predicted in the absence of adequate data. Hence a study that traces the variation in physical and chemical properties and nutrient status of teak soils with age of plantations, till the end of a rotation period is highly pertinent. The data generated by such a study will be more useful if accompanied by information on soil changes following a short rotation plantation crop. Eucalypt, a major short rotation crop in Kerala, was chosen for this purpose. Taking into account the importance of micronutrients to productivity, the variability in micronutrients with different age classes in teak and rotations in eucalypt was also studied.

Organic matter is the most important constituent of soil and its composition depends upon the nature of vegetation. Replacement of natural forest by monoculture plantations may not only change the quantity of organic matter in soils but also its quality. Thus, a comparison of soil organic matter fractions in natural forest and plantations of teak and eucalypt will enhance our understanding of these ecosystems. This study was thus intended

1. to compare the soil physical and chemical properties in teak of varying age classes and eucalypt plantations of different rotations with those of natural forest

2. to evaluate the micro nutrient status of soils in teak plantations of varying age classes and eucalypt plantations of different rotations with those of natural forest

3. to characterize and assess the soil organic matter (OM) fractions in these soils

4. and to evaluate the overall impact of plantation activities on soils

The study was carried out in the South Indian moist deciduous forest and teak (*Tectona grandis Linn. F*)and eucalypt (*Eucalyptus tereticornis Sm.*) plantations. They were in Vazhachal Forest Division for teak and in Thrissur Forest Division for eucalypt in the highlands of Kerala.

To compare the soil properties in different aged teak plantations with that of natural forest, age classes were developed as base line. Plantations were aggregated into four age classes *viz.* 21-30, 31-40, 41-50 and > 51 years. As there was a ban for clearfelling of natural forest since 1980, first rotation plantations of 1-10 and 11-20 year age classes were not available. As plantations of all age classes satisfying the above mentioned criteria were not available in one location, younger age teak plantations *viz.* 21-40 years were selected in Karadipara and older age teak plantations *viz.* 41-50 and >51 years were chosen at Athirapilly. The moist deciduous forest adjacent to the teak plantations in both locations were selected as a reference stand. A total of 26 sample plots in teak plantations and 10 sample plots in natural forest were laid out.

To compare the soil properties in eucalypt plantations belonging to different rotations with that of natural forest, second and third rotation plantations were selected. Two third rotation plantations, one coppiced and a replanted plantation were included in the study. A total of 15 sample plots in teak plantations and 5 sample plots in natural forest were laid out.

Only plantations which were adjacent to, or in close proximity with moist deciduous forest were chosen. Three composite soil samples from 0-20, 20-40 and 40-60cm depths were collected from each sample plot. A composite surface sample was also collected from the oldest teak and eucalypt plantation and adjacent natural forests. A total of 188 soil samples were collected.

Soil samples were subjected to physical and chemical analysis. Gravel content, particle-size separates, bulk density, particle density and maximum water holding capacity, soil pH, exchangeable bases, organic carbon, total nitrogen, exchangeable sodium, potassium, calcium, magnesium, phosphorus, iron, copper, manganese and zinc were determined. Surface samples were subjected to proximate analysis for determining the fats and waxes, resins, free sugars, hemicellulose, cellulose, lignin and protein contents in soils. The conclusions of the study are:

- In natural forest, gravel contents and bulk density increased and water holding capacity and pore space values decreased with depth. Such a clear trend was not noticed in plantations, which is an indication of their disturbed status.

- When the effect of monoculture plantations on soils as a whole was studied, it was observed that soils of plantations had higher gravel contents than natural forest. In teak plantations, as the plantations grew old, a general trend of decline in relative gravel per cent with age was observed. Such a trend was not observed in eucalypt plantations.

- Soils in plantations had higher amount of coarse fragments and lower amount of fine fractions than soils in the natural forest and were more compacted. Greater compaction was observed in plantations of eucalypts than teak. In teak plantations, an increase in bulk density values with age in younger ones and stabilization in older plantations was noticed. Such a trend was not observed in eucalypt.

- Soils in the plantations, generally, had higher particle density and lower pore space values than natural forest. A significant decrease in pore space was limited to 0-20cm depth in teak, while in eucalypt, the difference was significant in the

0-60cm depth. Water holding capacity values in plantation soils was lower than that of natural forest though the difference was significant only in younger teak plantations in the 0-60cm depth. On the other hand, all the plantations of eucalypt had significantly lower water holding capacity values than natural forest.

When soils in natural forest, teak and eucalypt were compared, it was observed that plantation activity changed soil pH. Soils in teak showed an increase in soil pH values while those in eucalypts recorded a decrease in pH values. Exchangeable bases in soils of teak plantations and natural forest did not differ significantly from each other, although a significant decline was noticed in eucalypt plantations.

The effect of eucalypt plantations on exchangeable sodium in soil was more pronounced than that of teak. A small but significant increase in exchangeable sodium was observed in the oldest age class teak plantations. In eucalypt, the values were significantly higher in third rotation plantations.

Plantation activity had no outstanding effect on exchangeable potassium though a small but significant decrease was observed in soils of older teak plantations. Teak and eucalypt plantations differed in their effect on soil exchangeable calcium. A significant decline in exchangeable calcium was observed in eucalypt plantations in the 0-60cm depth. On the other hand, in teak, no such difference was observed.

A slight decrease in the availability of phosphorus was observed in older teak plantations relative to natural forest whereas in eucalypt plantations an increase with rotation was observed.

Soils in teak and eucalypt plantations were poorer in organic carbon than those in the natural forest and the difference was most pronounced in the upper layer. In teak plantations, soil organic carbon was found to decrease initially and then increase with age. In eucalypt, such a pattern of variation was not observed. Organic carbon in soils decreased with rotation, though an increase was observed in replanted plantations relative to coppiced one.

Total nitrogen in plantation soils was lower than that of natural forest. The difference was significant in eucalypt plantations and non significant in teak. In plantations of eucalypt, total nitrogen decreased with rotation.

The values for exchangeable iron in plantations of eucalypt were significantly higher than that of natural forest and the values increased with rotation. However, in teak plantations, an initial increase was followed by a decrease in the older plantations in the 0-60cm depth. Exchangeable iron was found to be negatively correlated with organic carbon and the change in iron status of plantation soils may be mediated through soil organic carbon. Soils in teak plantations were richer in exchangeable copper than natural forest whereas those of eucalypt were poorer. The difference from natural forest was significant in both plantations in the 0-60cm depth.

Soils in teak and eucalypt plantations and natural forest did not differ significantly from each other with respect to exchangeable zinc status. Availability of manganese in eucalypt plantation soils decreased with rotation. The difference from natural forest values was significant in the third rotation in the 0-60cm depth. In plantations of teak, such a clear pattern or significant difference was not seen.

Fats and waxes, free sugar, hemicellulose, cellulose, protein and lignin contents in soils of monoculture plantations were significantly lower than that of natural forest. Resin contents in eucalypt plantations were significantly higher than both natural forest and plantations of teak.

- Factor analysis on soils of natural forest and teak plantation led to a five factor model which accounted for 67.1 per cent of total variation in soil properties. These were fertility and compaction factor, texture factor, micronutrient factor, potassium factor and exchangeable bases factor.

- The difference in soil properties between natural forest and eucalypt was explained by a four factor model that accounted for 71.2 per cent of variation. The factors were fertility, nutrient capital and compaction factor, texture factor, magnesium factor and potassium and zinc factor.

- When fertility index values for teak and eucalypt plantations were compared, it could be concluded that loss of fertility was greater in eucalypt plantations than in teak. In plantations of eucalypt, fertility decreased with rotation. It was also observed that, in plantations of teak, fertility initially decreased and then increased with age of the plantation. An increase in soil fertility in teak plantations was apparent only after 40 years of its establishment.

- From the foregoing, it is proved that the soil health in teak plantations of varying age classes and eucalypt plantations of different rotations were lower than those in the natural forest. Over time, soils started recuperating in teak plantations when compared to eucalypt where continuous degradation over rotation takes place. Within a rotation period, in teak plantations, recuperation starts around 40Y onwards after establishment. Whether this phenomenon prevails or not in successive rotations in teak and in other agro ecological zones have to be studied in detail.

List of Abbreviations

Y - Year

MSL - Mean Sea Level

ha. - Hectare

NF – Natural Forest

TP – Teak Plantation

E – Eucalypt

C – Coppiced

R - Replanted

G - Gravel

S - Sand

Si -Silt

Cly - Clay

Wt. - Weight

BD - Bulk Density

PD - Particle Density

PS - Pore Space

WHC - Water Holding Capacity

Ex. Bases - Exchangeable bases

Ex. Na – Exchangeable Sodium

Ex. K – Exchangeable Potassium

Ex. Ca – Exchangeable Calcium

Ex. Mg – Exchangeable Magnesium

Av. P – Available phosphorus

OC – Organic carbon

Total N Total Nitrogen

C/N Carbon/Nitrogen

Ex. Fe – Exchangeable Iron

Ex. Mn - Exchangeable Manganese

Ex. Cu – Exchangeable Copper

Ex. Zn – Exchangeable Zinc

T.V. – Titer value

ANOVA – Analysis of Variance

SPSS – Statistical Programme for Social Sciences

References

References

Aborisade, K. D. and Aweto, A. O. 1990. Effects of exotic tree plantations of teak (*Tectona grandis*) and gmelina (*Gmelina arborea*) on a forest soil in south-western Nigeria. *Soil Use and Management*, 6: 43-45.

Alexander, T. G., Balagopalan, M., Thomas, T. P. and Mary, M. V. 1981. Properties of soils under teak. KFRI Research Report No.7. 13p.

Allan, T. and Lanly, J. P. 1991. Overview of status and trends of world forest. *In*: Technical workshop to explore options for global forestry management. D. Howlett and C. Sargent (eds.). International Institute for Environment and Development, London, pp.17-39.

Amponsah, I. and Meyer, W. 2000. Soil characteristics in teak plantations and natural forests in Ashanti region, Ghana. Communications in *Soil Science and Plant Analysis*, 31: 355-373.

Anonymous. 1997. Kerala State Resource based Perspective Plan 2020AD. Kerala State Land Use Board, Vikas Bhavan Thiruvananthpuram. pp.22-23.

Arias, Luis Ugalde. 2003. Advancement in management and productivity of teak in Central America. *In*: Quality timber products of teak from sustainable forest management. Proceedings of the international conference on Quality timber products of teak from sustainable forest management. K. M. Bhatt, K. K. N. Nair, K. V. Bhatt, E. M. Muralidharan and J. K. Sharma (eds.) Kerala Forest Research Institute, Peechi. pp.92-103.

Armstrong, D. E. and Chesters, G. 1964. Properties of protein- bentonite complexes as influenced by equilibrium conditions. *Soil Science*, 98: 39-52.

Ashworth, M. R. F. 1942. The fractionation of the organic matter, including nitrogen, of certain soils and its relation to their quality. *Journal of Agricultural Sciences Cambridge*, 32: 349-359.

Aweto, A. O. 1981. Secondary succession and soil fertility restoration in south western Nigeria: II. Soil fertility restoration. *The Journal of Ecology*, 69: 609-614.

Aweto, A. O. 2001. Impact of single species tree plantations on nutrient cycling in West Africa. *International Journal of Sustainable Development and World Ecology*, 8: 356-368.

Baber, S., Ahmad, M. F. and Bhatti, A. 2006. The effect of *Eucalypts Camaldulensis* on soil properties and fertility. *Journal of Agricultural and Biological Science*, 1: 47-50.

Balagopalan, M. 1987. Properties of soils in natural forests and plantations of Trivandrum forest Division. Division of Soil Science. Kerala Forest Research Institute, Peechi. 97p.

Balagopalan, M. 1991. Studies on Soil Organic Matter. Ph.D. Thesis Calicut University. 247p.

Balagopalan, M. 1992. Impact on soils of growing Eucalypts in Kerala. Seminar on Environmental Problems of Kerala. 2nd December. Center for Water Resources Development and Management. Kozhikode, Kerala.

Balagopalan, M. 1995a. Soil characteristics in natural forests and *Tectona grandis* and *Anacardium occidentale* plantations in Kerala, India. *Journal of Tropical Forest Science*. 7: 635-644.

Balagopalan, M. 1995b. Effect of differences in forest cover on the variation in soil properties in Kerala, India. *Journal of Tropical Forestry*. 11: 125-131.

Balagopalan, M. and Alexander, T. G. 1984. Soil organic carbon distribution along a transect through teak, eucalypt and albizia plantations in Kerala. *Journal of Tropical Forestry*, 12: 33-37.

Balagopalan, M. and Geetha, T. 2006. Changes in organic matter and sulphur contents and their interrelationships in different vegetation types in Kerala, India. *Advances in Plant Sciences*, 19: 93-98.

Balagopalan, M. and Jose, A. I. 1982a. Dynamics of organic carbon and different forms of nitrogen under first and second rotation teak plantations of Kerala. *Agricultural Research Journal of Kerala*, 20: 92-97.

Balagopalan, M. and Jose, A. I. 1982b. Distribution of organic carbon and forms of nitrogen in soil under Mahagony and Teak. *Agricultural Research Journal of Kerala*. 20: 16-21.

Balagopalan, M. and Jose, A. I. 1983. Changes in organic carbon and different forms of Nitrogen under first and second rotation coppiced Eucalypts plantations. *Agricultural Research Journal of Kerala*, Research Notes. 21: 57-62.

Balagopalan, M. and Jose, A. I. 1986. Distribution of organic carbon and different forms of nitrogen in a natural forest and adjacent eucalypts plantation at Arripa, Kerala. *In*: Eucalypts in India: Past, Present and future. J. K. Sharma, C. T. S. Nair, S. Kedarnath and S. Kondas (eds.) Kerala Forest Research Institute. Peechi. pp. 112-119.

Balagopalan, M. and Jose, A. I. 1993. A comparative study on the properties of soils in relation to vegetational types. *Journal of Tropical Agriculture*, 31: 167-173.

Balagopalan, M. and Jose, A. I. 1995. Soil chemical characteristics in a natural forest and adjacent exotic plantations in Kerala, India. *Journal of Tropical Forest Science*, 8: 161-166.

Balagopalan, M. and Jose, A. I. 1997. Effect of tree species on soil properties along a transect through teak, eucalypt and rubber in Kerala. *In*: Teak. Proceedings of the International Teak Symposium. S. Chand Basha, C. Mohan and S. Sankar (eds). Kerala Forest Research Institute, Peechi. pp. 236-241.

Balagopalan, M., Thomas, T. P., Mary, M. V., Sankar, S. and Alexander, T. G. 1992. Soil properties in teak, bombax and eucalypt plantations of Thrissur Forest Division, Kerala. *Journal of Tropical Forest Science*, 5: 35-43.

Banerjee, S. P. and Badola, K. C. 1980. Nature and properties of some Deodar (*cedrus deodara*) forest soils of Chakrata Forest Division, U.P. *Indian Forester*, 106: 558-560.

Bargali, S. S. and Singh, S. P. 1991. Aspects of productivity and nutrient cycling in a eight year old Eucalypts plantation in a moist plain area adjacent to central Himalaya India. *Canadian Journal of Forest Research*, 21: 1365-1372.

Bargali, S. S. and Singh, S. P. 1995. Dry matter dynamics, storage and flux of nutrients in an aged eucalypt plantations. *Oecologia Montana*, 4: 9-14.

Bargali, S. S., Singh, R. P. and Joshi, M. 1993. Changes in soil characteristics in eucalypt plantations replacing natural broad-leaved forests. *Journal of Vegetation Science*, 4: 25-28.

Bell, T. I. W. 1973. Erosion in Trinidad teak plantations. *Commonwealth Forestry Review*, 52: 223-233.

Bhoumik, L. K. and Totey, N. G. 1990. Characteristics of some soils under Teak Forests. *Journal of Indian Society of Soil Science*, 38: 481 487.

Binkley, D. 1986. Forest Nutrition Management. Wiley, New York. 290p.

Binkley, D., O'Connell, A. M., Sankaran, K. V. and Nambiar, E. K. S. 1997. Stand development and productivity. *In*: Management of Soil Nutrients and Water in Tropical Plantation Forests. Brown, A. G. (eds.). ACIAR monograph No. 43: 443-480.

Black, C. A., Evans, D. D., Ensminger, L. E., White, J. L. and Clark F. E. 1965. Methods of Soil Analysis. Part I. American Society of Agronomy. Inc., Madison, Wisconsin, USA. 770p.

Braids, O. C. and Miller, R. H. 1975. Fats, waxes and resins in soils. *In*: Soil Components. Volume I. Organic Components. John E. Geiesking (ed.), Springer – Verlag New York Inc. pp. 343-368.

Bray, R. H. and Kurtz, L. T. 1945. Determination of total organic and available forms of phosphorus in soils. *Soil Science*, 59: 39-45.

Chacko, K. C. 1998. Silvicultural problems in management of teak plantations. *In*: Teak for the Future - Proceedings of the Second Regional Seminar on Teak. 29 May-June 3, 1995. Myanmar. Kashio, M and White, K.Yagon. (eds.) FAO regional office for Asia and Pacific Bangkok. pp. 91- 98.

Champion, H. G. 1932. The problem of pure teak plantations. *Indian Forest Bulletin*. 78p.

Chamshama, S. A. O., Mugasha, A. G. and Sanga, J. M. 2000. Comparison of some chemical properties of soil under teak and natural forests at Mtibwa, Morogoro, Tanzania. *Journal of Tropical Forest Science*, 12: 92-103.

Chand Basha, S. 1986. Performance of eucalypts in Kerala. *In*: Eucalypts in India: Past, Present and Future. J. K. Sharma, C. T. S. Nair, S. Kedarnath and S. Kondas (eds.) Kerala Forest Research Institute. Peechi. pp. 71-76.

Chaubey, O. P., Ram Prasad and Mishra, G. P. 1988. Litter production and nutrient return in teak plantations and adjoining natural forests in Madhya Pradesh. *Journal of Tropical Forestry*, 4: 242-255.

Chavan, K. N., Kenjale, R. Y. and Chavan, A. S. 1995. Effect of forest tree species on properties of lateritic soil. *Journal of Indian Society of Soil Science*, 43: 43-46.

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

Dalal, R. C. and Henry, R. J. 1988. Cultivation effects on carbohydrates contents of soil and soil fractions. *Soil Science Society of America Journal*, 52: 1361-1365.

Dan, B., Richard, F. Fisher and William, L. Pritchett. 2000. Ecology and Management of Forest Soil. John Wiley and Sons. 512p.

Das, D. K. and Agrawal, R. P. 2002. Physical properties of soil. *In*: Fundamentals of Soil Science. Sekhon, G. S., Chhonkar, P. K., Das, D. K., Goswami, N. N., Narayanasamy, G., Poonia, S. R., Rattan and R. K., Sehgal, J. (eds.) Indian Society of Soil Science New Delhi. pp. 71-92.

Davis, P. W. 1940. Preliminary note on Nilambur soils with special reference to their suitability for Teak. *Indian Forester*, 66: 658-671.

Deb, D. L. and Sakal, R. 2002. Micronutrients. *In*: Fundamentals of Soil Science. Sekhon, G. S., Chhonkar, P. K., Das, D. K., Goswami, N. N., Narayanasamy, G., Poonia, S. R., Rattan and R. K., Sehgal, J. (eds.) Indian Society of Soil Science, New Delhi. pp. 391-404.

Dell, Bernie, Daping Xu, Catherine Rogers and Longbin Huang. 2002. Micronutrient Disorders in Eucalypt Plantations: Causes, Symptoms, Identification, Impact and Management. *In*: Eucalypts Plantations: Research, Management and Development. Proceedings of the International Symposium. 1-6 September, Guangzhou, China.

Dhanya, M. B., Balagopalan, M., Rugmini, P., Geetha, T. and Chandramohana Kumar. N. 2006. Variation in soil organic carbon and micronutrient status in teak plantations under different rotations in Kerala. *Journal of soils and Crops*, 16: 17-24.

Evans, Julian. 2000. Sustainability of productivity in Successive rotations. Proceedings of the international conference on timber plantation development. FAO Corporate Document Repository: 1-19.

FAO. 1995. Forest Resources Assessment, 1990-Global Synthesis. FAO Forestry Paper 124. Food and Agriculture Organization of the United Nations, Rome.

Field. A. 2000. Exploratory Factor Analysis. *In*: Discovering Statistics Using SPSS for Windows. Sage Publications. London. pp. 423-470.

Folster, H. and Khanna, P. K. 1997. Dynamics of nutrient supply in plantation soils. *In*: Management of soil, water and nutrients in tropical plantation forests. E. K. S. Nambiar and A. G. Brown (eds.) Australian Centre for International Agriculture Research (ACIAR), monograph 43, Canberra. pp. 339-378.

Gama, R. A. C., Barros, N. F. and Mendonca, E. S. 1999. Edaphic alterations under pure and mixed stands of tree species in southeastern Bahia state, Brazil. *Revista-Brasileira-de-Ciencia-do-Sol*, 23: 581-592.

Geetha, T. and Balagopalan, M. 2005a. Variation in soil physical properties associated with different year teak plantations in Kerala. *Journal of Soils and Crops*, 15: 264-268.

Geetha, T. and Balagopalan, M. 2005b. Soils as influenced by teak and eucalypt plantations – A case study in Peechi- Vazhani wild life sanctuary, Kerala. *Journal of Soils and Crops*, 15: 240-246.

Geetha, T. and Balagopalan, M. 2006. Decline in soil productivity associated with plantation forest ecosystem in Kerala. *In:* National Conference on Forest Biodiversity Resources: Exploitation, Conservation and Management, held during 21 – 22, March 2006, organized by Center for Biodiversity and Forest Studies, Madurai Kamaraj University, Madurai - 625021, Tamil Nadu. pp. 87-88.

Goncalves, J. L. M., Barros, N. F., Nambiar, E. K. S. and Novais, R. F. 1997. Soil and stand management for short rotation plantations. *In*: Management of soil, water and nutrients in tropical plantation forests. E. K. S. Nambiar and A. G. Brown (eds.) Australian centre for International agriculture Research (ACIAR), monograph 43, Canberra. pp. 379-417.

Gopikumar, K., Varghese, V. and Vidyasagar, K. 2001. Nutrient deficiency studies in teak (*Tectona grandis* Linn.,) seedlings. Proceedings of the thirteenth Kerala Science Congress. M.R. Das (ed.) State Committee on Science, Technology and Environment, Kerala..

Ghosh, K. and Bhardwaj, K. K. R. 2002. Soil Organic Matter. *In*: Fundamentals of Soil Science. Sekhon, G. S., Chhonkar, P. K., Das, D. K., Goswami, N. N., Narayanasamy, G., Poonia, S. R., Rattan and R. K., Sehgal, J. (eds.) Indian Society of Soil Science, New Delhi. pp. 455-464.

Greenland, D. J. and Oades, J. M. 1975. Saccharides. *In*: Soil Components. Volume I Organic Components. John E. Geiesking (ed.).Springer – Verlag New York Inc. pp. 213-262.

Greig Smith, R., 1910. Contributions to our knowledge of soil fertility. 1. The action of wax solvents and the presence of thermolabile bacteriotoxins in soils. *Proceedings of. Linnaean Society New South Wales,* 35: 808.

Griffith, A. L. and Gupta, R. S. 1948. Soils in relation to Teak with special reference to laterization. *Indian Forester. Bulletin* No. 141. pp. 58.

Guo Jian Fen, Xie Jin Sheng, Lu HaoLiang, Liu Dong Xia, Yang Yu Sheng and Chen Guang Shui. 2004. Carbon return and dynamics of litterfall in natural forest and monoculture plantation of Castanopsis kawakamii in subtropical China. *Forestry Studies in China*, 6: 33-36.

Gupta, R. S. 1956. On the suitability of soils for Teak plantations with special reference to laterization. Proceedings of 8th silver jubilee Conference, 1951. Part 2. Dehra Dun. pp. 266-269.

Harman, H. H. 1976. Modern Factor Analysis. 3rd revised ed. University of Chicago Press, 487p.

Havlin, J. L., Beaton, J. D., Tisdale, S. L. and Nelson, L. W. 2003. Micronutrients. *In*: Soil Fertility and Fertilizers. An Introduction to Nutrient Management. Pearson Education (Singapore) New Delhi. pp. 245-299.

Hesse, P. R. 1971. A Text Book of Soil Chemical Analysis. John Murray Publishers, London. 520 p.

Hussein, A. K. M. A., Raison, R. J. and Khanna, P. K. 1995. Effect of fertilizer application and fire regime on soil microbial biomass carbon and nitrogen, and nitrogen mineralization in an Australian sub alpine eucalypt forest. *Biology and fertility of soil*, 19: 246-252.

Hosur, G. C. and Dasog, G. S. 1995. Effect of tree species on soil properties. *Journal Indian Society of Soil Science*, 43: 256-259.

Huntington, T. G., Ryan, D. F. and Hamburg, S. P. 1988. Estimating soil nitrogen and carbon pools in a northern hardwood forest ecosystem. *Soil Science Society of American Journal*, 52: 1162-1167

Jackson, M. L. 1958. Soil Chemical Analysis. Prentice Hall Inc., U.S.A. 498p.

Jaiyeoba, I. A. 1995. Changes in soil properties related to different land uses in part of the Nigerian semi arid savannah. *Soil Use and Management*, 11: 84-89.

James, F. C. and McCulloch, C. E. 1990. Multivariate analysis in ecology and systematics: Panacea or Pandora's box. Annals of Rev. Ecol. Syst. 21: 126-166.

Jha, M. N., Dimri, B. M. and Gupta, M. K. 1996. Soil nutrient changes under different ages Eucalypts monoculture. *Indian Forester*, 122: 55-60.

Jha, M. N., Gupta, M. K. and Rajeev Pande. 2000. Factor analysis of soil nutrient distribution pattern under different plantations. *Indian Forester*, 130: 1270-1278.

Jhorar, L. R., Dashing Singh, Agrawal, R. P. and Jagan Nath. 1993. Changes in some soil physical properties under different geometry of eucalypts plantation. *Haryana Agricultural University Journal of Research*, 23: 83-89.

Jianwei Li, Daniel Richter, Arlene Mendoza and Paul Heine 2006. Thirty five year changes in soil Mn, B, Cu and Fe in response to forest growth. 18^{Th} World Congress of Soil Science. July 9-15, 2006-Philadelphia, Pennsylvania, USA.

Johannes, M. H. Knops and Tilman, David. 2000. Dynamics of soil nitrogen and carbon accumulation for 61 Years after agricultural abandonment. *Ecology*, 81: 88-98.

Johnson, R. A. and D. W. Wichern. 1992. Applied Multivariate statistical analysis. Prentice - Hall, Eaglewood Cliffs, New Jersy.

Johnson, W. D. 1992. Effects of forest management on soil carbon storage. *Water, Air and soil pollution*, 64: 83-120.

Jose, A. I. and Koshy, M. M. 1972. A study of the morphological, physical and chemical characteristics of soils as influenced by teak vegetation. *Indian Forester*, 98: 338-348.

Joshi, M., Bargali, K. and Bargali, S. S. 1997. Changes in physico-chemical properties and metabolic activity of soil in poplar plantations replacing natural broad-leaved forests in Kumaun Himalaya. *Journal of Arid Environments*, 35: 161-169.

Kaiser, H. F. 1970. A Second Generation Little Jiffy. *Psychometrika*, 35: 401-415.

Kaiser, H. F. 1974. An Index of Factorial Simplicity. *Psychometrika*, 35: 401-415.

Kamala, B. S., Angadi, V. G., Parthasarathi, K. and Ravi, S. N. 1986. Symptoms of deficiency of trace elements and the assossiated changes in peroxidase isoenzyme pattern in the seedlings of teak, mahagony and eucalyptus. *Van -Vigyan*, 24: 49-55.

Karia, J. P. and Kiran, G. S. 2004. Physico-Chemical properties of forest soils of Chhotaudepur Division. *Indian Forester*, 130: 1031-1039.

Karmacharya, S. B. and Singh, K. P. 1992. Biomass and net production of teak plantations in a dry tropical region in India. *Forest Ecology and Management*, 55: 233-247.

Katwal, R. P. S. 2003. Teak in India: Status, Prospects and Perspectives. *In*: Quality timber products of teak from sustainable forest management. Proceedings of the international conference on Quality timber products of teak from sustainable forest management. K. M. Bhat, K. K. N. Nair, K. V. Bhat, E. M. Muralidharan and J. K. Sharma (eds.) Kerala Forest Research Institute, Peechi. pp.1-18.

Kondas, S. and Venkateshan, K. R. 1986. *Eucalyptus* in Tamil Nadu. In: *Eucalypts* in India-Past, present and future, Proceedings of the national seminar on Eucalypts in Indian forestry - Past, Present and Future held at Kerala Forest Research Institute, Peechi, on January 30-31, 1984. (eds.) J. K. Sharma, C. T. S. Nair, S. Kedarnath, S. Kondas. pp. 31-35.

*Korschens, M. and Greilich, J. 1981. Relationships between organic matter, particle density and bulk density of soil. *Archiv Fur Ackerund pflanzenbau und Boden Kunde*, 25: 519-523.

Kaosa-ard, A. 1998. Overview: Problems in teak plantation establishment. *In*: Teak for the Future - Proceedings of the Second Regional Seminar on Teak. 29 May- June

3, 1995. Kashio, M and White, K. (eds.) Yagon. Myanmar. FAO. Regional office for Asia and Pacific. Bangkok. 249p

Krishnapillay, B. 2000. Silviculture and management of teak plantations. *Unasylva* No. 201 . 51: 2.

Lal, R. 1973. Soil erosion and shifting agriculture. Shifting Cultivation and Soil Conservation in Africa, FAO Soils Bulletin 24: 48-71.

Laurie, M. V. and Griffith, A. L. 1942. The problem of the pure Teak plantation. *Indian Forester Rec. (n.s.) Silviculture*, *5*: 1-121.

Lian-Yu Wu and Zhang-Qi Shui. 1998. Conversion of a natural broad-leafed evergreen forest into pure and mixed plantation forests in a subtropical area: effects on nutrient cycling. *Canadian Journal of Forest Research*, 28: 1518-1529.

Lundgren, 1978. Soil conditions or nutrient cycling under natural and plantations forests in Tanzanian Highlands. Reports no. 31. Swedish University of Agricultural Science 426 p.

Maharudrappa, A., Srinivasamurthy, C. A., Nagaraja, M. S., Siddaramappa, R. and Anand, H. S. 2000. Decomposition rates of litter and nutrient release pattern in a tropical soil. *Journal of Indian Society of Soil Science*, 48: 92-97.

Malewar, G. U. 2005. Micronutrient stress in soils and crops: serious sickness and clinical approaches for sustainable agriculture. *Journal of the Indian Society of Soil Science*, 53: 484-499.

Mandal, A. K., Nath, S., Gupta, S. K. and Banerjee, S. K. 1990. Characteristics and nutritional status of soils of middle hill and upper hill forest of the eastern Himalayas. *Journal of Indian Society of Soil Science*, 38: 100-106.

Mapa, R. B. 1995. Effect of reforestation using Tectona grandis on infiltration and soil water retention. *Forest Ecology and Management*, 77: 119-125.

Maro, R. S., Chamshama, S. A. O., Nsolomo, V. R. and Maliondo, S. M. 1993. Soil chemical characteristics in a natural forest and a *Cupressus Lusitanica* Plantation at west Kilimanjaro. Northern Tanzania. *Journal of Tropical Forest Science*, 5: 465-472.

Marquez, O., Hernandez, R., Torres, A. and Franco, W. 1993. Changes in the physicochemical properties of soils in a chronosequence of *Tectona grandis*. *Turrialba*. 43: 37-41.

McLaren, A. D. 1954. The adsorption and reactions of enzymes and proteins on Kaolinite. II. Journal of Physical Chemistry 58: 129-137.

Michelsen, A., Lisanework, N., Friis, I. and Holst, N. 1996. Comparisons of under storey vegetation and soil fertility in plantations and adjacent natural forests in the Ethiopian highlands. *Journal of Applied Ecology*, 33: 627-642.

Mishra, A., Sharma, S. D., and Khan, G. H. 2003. Improvement in Physical and chemical properties of sodic soil by 3, 6 and 9 years old plantations of *Eucalyptus tereticornis* Biorejuvenation of sodic soil. *Forest Ecology and Management,* 184: 115-124.

Mongia, A. D. and Bandyopadhyay, A. K. 1992a. Physicochemical changes occurring in soils of tropical forest after clearfelling for high value plantation crops. *Journal of the Indian Society of Soil Science*, 40: 420-424.

Mongia, A. D. and Bandyopadhyay, A. K. 1992b. Distribution of different forms of copper under different vegetations. *Journal of the Indian Society of Soil Science*, 40: 851-853.

Mongia, A. D. and Bandyopadhyay, A. K. 1994. Soil nutrients under natural and planted forest in island ecosystem. *Journal of Indian Society of Soil Science,* 42: 43-46.

Moran, Emilio F., Brondizio, Eduardo S., Tucker, Joanna M., Forsberg, Maria Clara da Silva, Stephen McCracken and Falesi Italo, 2000. Effects of soil fertility and land-use on forest succession in Amazonia. *Forest Ecology and Management,* 139: 93-108.

Nagesh Prabhu, 2003. Teak in Kerala State, India: Past, Present and Future. In: Quality Timber Products of Teak from Sustainable Forest Management. Proceedings of the international conference on Quality timber products of teak from sustainable forest management. K. M. Bhat, K. K. N. Nair, K. V. Bhat, E. M. Muralidharan and J. K. Sharma (eds.). Kerala Forest Research Institute, Peechi. pp.1-18.

Nath, S., Banerje, M., Chattoraj, G., Ganguly, S. K. and Banerjee, S. K. 1988. Changes in soil attributes consequent up on differences in forest cover in a plantation area. *Journal of Indian Society of Soil Science*, 36: 515-521.

Nair, C. T. S. 1998. Discussion on Teak Plantation Establishment. *In*: Teak for the Future - Proceedings of the Second Regional Seminar on Teak. 29 May- June 3, 1995. Kashio, M and White, K. (eds.). Yagon. Myanmar. FAO. Regional office for Asia and Pacific Bangkok. 249p.

Negi, J. D. S., Bahuguna, V. K. and Sharma, D. C. 1990. Biomass production and distribution of nutrients in 20 years old teak (*Tectona grandis*) and Gamar (*Gmelina arborea*) plantation in Tripura. *Indian forester*, 116: 681-686.

Negi, M. S., Tandon, V. N. and Rawat, H. S. 1995. Biomass and nutrient distribution in young teak (*Tectona grandis Linn. F*) plantations in Tarai region of Uttar Pradesh. *Indian-Forester*, 121: 455-464.

Nitant, H. C., Bhushan, L.S. and Inder Pal. 1992. Status of soil properties in Yamuna ravines under forest cover. *Journal of Tropical Forestry*, 8: 31-37.

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

Nwoboshi, L. C. 1984. Growth and nutrient requirements in a Teak Plantation age series in Nigeria. II Nutrient accumulation and minimum annual requirements. *Forest Science*. 30: 35-40.

O'Brien, N. D., Attiwill, P. M. and Weston, C. J. 2003. Stability of soil organic matter in Eucalypts regnans forests and Pinus radiata plantations in south eastern Australia. *Forest Ecology and Management*, 185: 249-261.

O'Connell, A. M, Sankaran, K.V. and Nambiar, E. K. S. 1997. Organic matter accretion, decomposition and mineralization. *In*: Management of Soil Nutrients and Water in Tropical Plantation Forests. A. G. Brown, (eds.). ACIAR monograph No. 43: 443-480.

Okoro, S. P. A., Aighewi, I. T. and Osagie, C. O. 1999. Effects of selected monoculture plantation species on the humid tropical soils of Southern Nigeria. *Nigerian Journal of Forestry*, 29: 73-79.

Okoro, S. P. A., Aighewi, I. T. and Osagie, C. O. 2000. Effect of selected monoculture plantation species on the humid tropical soils of southern Nigeria. *Indian Journal of Agricultural Science*, 70: 105-109.

Page, A. L., Miller, R. H. and Keeney, D. R. 1982. Methods of Soil Analysis. Part II. American Society of Agronomy. Inc., Madison, Wisconsin, USA. 728p.

Panda, A. and Swain, S. L. 2002. Leaf litter decomposition of teak, acacia and eucalypts in plantation forest of Orissa. *Journal of Ecobiology*, 14: 223-231.

Pande, P. K. 1999. Litter decomposition in tropical plantations: impact of climate and substrate quality. *Indian Forester*, 125: 599-607.

Pande, P. K. 2004. Temporal variations in soil nutrients under tropical plantations. *Annals of Forestry*, 12: 29-37.

Pande, P. K. and Sharma, S. C. 1993a. Litter decomposition in some plantations (India). *Annals of Forestry*, 1: 90-101.

Pande, P. K. and Sharma, S. C. 1993b. Biochemical cycling and nutrient conservation strategy in some plantations. *Indian Forester*, 119: 299-305.

Piper, C. S. 1942. Soil and Plant Analysis. Hans publishers, Bombay. 368p.

Polglase, P. J., Paul, K. I., Khanna, P. K., Nyakuengama, J. G., O'Connell, A. M., Grove, T. S. and Battaglia, M. 2000. Change in organic carbon following afforestation or reforestation-Review of experimental evidence and development of a conceptual framework. National Carbon Accounting System Technical Report No. 20. Australian Greenhouse Office, Canberra.

Prathiban, K. T. and Rai, R. S. V. 1994. Effect of few soil species on soil physical properties. *Journal of Tropical Forest Science*, 6: 223-229.

*Purwanto. 1990. Effects of some forest tree monoculture stands on soil physical and chemical properties . Bulletine – Penelitian – Hutan. No. 531- 11-31.

Rahman, M. H, and Elahi, S. 2006. Distribution of some micronutrients in four pedons of Madhupur tract in Bangladesh. 18Th World Congress of Soil Science. July 9-15, 2006-Philadelphia, Pennsylvania, USA.

Rajagopal, C. K., Shriff, M. M., Selvakumari, G., Madappan, K. and Devarajan, R. 1974. Relation between organic carbon and available micronutrients in the soils of Nilgiris. *Journal of the Indian Society of Soil Science*, 22: 347-351.

Ram, N. and Patel, S. 1992. Infiltration capacity of compacted soil under teak plantation. *Van-Vigyan*, 30: 77-80.

Rathod, R. and Devar, K. V. 2003a. Effect of different plantations on soil physical properties. *Karnataka Journal of Agricultural Sciences*, 16: 487-488.

Rathod, R. and Devar, K. V. 2003b. Studies on the exchangeable nutrients of soil under different plantations. *Karnataka Journal of Agricultural Sciences*, 16: 489-490.

Rhoades, C. C. 1996. Single tree influences on soil properties in agroforestry: lessons from natural forest and savanna ecosystems. *Agroforestry-Systems*, 35: 71-94.

Rugmini, P. and Balagopalan, M. 2004. Soil nutrients as influenced by different natural vegetation types in the Western Ghats region of Kerala, India - Factor Analysis. *Advances in Plant Sciences*, 17: 597-603

Rugmini, P. and Balagopalan, M. 2006. Evaluation of factor patterns of soils in different plantations and natural forests in the Western Ghats, Kerala. *Indian Journal of Forestry*, 29: 271-275.

Sakal, R., Singh, A. P. and Singh, S. P. 1988. Distribution of available zinc, copper, iron and manganese in old alluvial soils as related to certain soil characteristics. *Journal of the Indian Society of Soil Science*, 36: 59-63.

Salifu, K. F. and Meyer, W. L. 1998. Physico-chemical properties of soils associated with logged forest and areas converted to teak (*Tectona grandis Linn. F*). in Ghana. *Commonwealth Forestry Review*, 77: 91-99, 157, 159-160.

Sangha, K. K. and Jalota, K. R. 2005. Value of ecological services of Exotic *Eucalypts tereticornis* and native *Dalbergia sisso* tree plantations of north-western India. *Conservation and Society*, 3: 92-109.

Sankaram. A. 1966. A laboratory manual for Agricultural Chemistry. Asia publishing house. India. 340 p.

Sankaran, K. V. 1993. Decomposition of leaf litter of albizia (*Paraserianthes alcataria*), eucalypt (*Eucalypts tereticornis*) and teak (*Tectona grandis*) in Kerala, India. *Forest Ecology and Management*, 56: 225-242.

Sankaran, K. V., Chacko, K. C., Pandalai, R. C., Kallarackal, J., Somen, C. K., Sharma, J. K., Balagopalan, M., Balasundaran, M., Kumaraswamy, S., Sankar, S., Gilkes, R. J., Grove, T. S., Mendham, D., O'Connell, A. M. 1999. Effect of site management on eucalypts plantations in the monsoonal tropics – Kerala. *In*: Site management and productivity in tropical plantation forests. A progress report. E. K. S. Nambiars, A. Tiarks, C. Cossalter and J. Ranger. (eds.) India Workshop proceedings 7-11 December. 1999. Kerala India. pp. 51-60.

Sujatha, M. P. 2003. Diagnosis of micronutrient deficiency in teak seedlings. KFRI Research Report No. 249. Kerala Forest Research Institute, Peechi. 29p.

Singh, M. V. 2004. Transfer of scientific knowledge to usable field practices. IFA International Symposium on Micronutrients. 23-25 February 2004, New Delhi, India.

Shetty, Vishwanathan, Narayanaswamy, C., Rudramurthy, H. V., Varghese, T. S. and Hegde, M. 2006. Available micronutrient status in traditional areca nut growing soils of Karnataka. 18Th World Congress of Soil Science. July 9-15, 2006- Philadelphia, Pennsylvania, USA.

Shyam Sunder, S. 1986. *Eucalyptus* in Karnataka - Past, present and future. *In*: *Eucalypts* in India-Past, present and future. Proceedings of the national seminar on Eucalypts in Indian forestry- Past, Present and Future held at Kerala Forest Research Institute, Peechi, Kerala, India. January 30-31, 1984. J. K. Sharma, C. T. S. Nair, S. Kedarnath and S. Kondas, (eds.). Kerala Forest Research Institute, Peechi. pp. 25-30.

Sikora, L. J., Yakovchenko, V., Camberdella, C. A. and Doran, J. W. 1996. Assessing soil quality by testing organic matter. *In*: Soil Organic Matter: Analysis and Interpretation. Special publication Soil Science Society of America (Ed.), No. 46, Madison, Wisconsin. pp. 41-50.

Silveira, R. L. V. de A., Luca, E. F. de, Silveira, L. V. de A., Luz, H. F. 2003. Dry matter, macronutrients concentration and content in *Eucalyptus grandis* seedlings according to the age. *Scientia Forestalis*, 64: 136-149.

Singh, D., Leelavathi, C. R., Krishnan, K. S. and Sarup, S. 1979. Monograph on crop response to micronutrients, IASRI, New Delhi., pp.1- 136.

Singh, O., Sharma, D. C. and Rawat, J. K. 1993. Production and decomposition of leaf litter in sal, teak, eucalypts and poplar forests in Uttar Pradesh. *Indian Forester*, 119: 112-121.

Singh, R. and Das, D. K. 1992. Wet ability of soil under different plant crops. *Journal of the Indian Society of Soil Scie*nce, 40: 39-43.

Singh, R., Singh, R. K., Kalyan Singh, Singh, R. and Singh, K. 1990. Effect of different plant covers on soil characteristics. *Indian Forester*, 116: 795-802.

Singh, S. and Singhal, R. M. 1974. Measurements of carbohydrates in the Acid hydrolysates of some outer Himalayan soils. *Journal of Indian Society of Soil Science*, 22: 290-293.

Singh, S. B., Prasad, K. G. and Banerjee, S. P. 1988. Chemical attributes in soils under different vegetations in semi-arid region. *Van-Vigyan*, 26: 96-97.

Singhal, R. M. 1986. Effect of growing eucalypts on the status of soil organic matter of Dehra dun forests. *In*: *Eucalypts* in India-Past, present and future, Proceedings of the national seminar on Eucalypts in Indian forestry- Past, Present and Future held at Kerala Forest Research Institute, Pecchi, on January 30-31, 1984. (eds.) J. K. Sharma, C. T. S. Nair, S. Kedarnath, S. Kondas. Kerala Forest Research Institute, Peechi. pp. 103-111.

Singhal, R. M. and Dev, S. 1977. Alteration in soil carbohydrates consequent upon growing *Eucalptus* in Natural Sal (*Shorea Robusta*) areas of Doon Valley. *Indian Forester*, 103: 403-410.

Singhal, R. M. and Sharma, S. D. 1983. Study of organic matter of some typical soils of Doon valley Forests. *Indian Journal of Forestry*, 6: 274-277.

Smethurst, P. J. and Nambiar, E. K. S. 1990. Distribution of carbon and nutrients and fluxes of mineral nitrogen after clear felling Pinus Radiata. *Canadian Journal of Forest Research*, 20: 1490-1497.

Sonkar, S. D. 2004. Litter production and nutrient return in the plantations of *Tectona grandis* and adjoining natural forest in Madhya Pradesh. *Environment and Ecology*, 22: 116-124.

Sree Ramulu, U. S. 2003. Principals in the quantitative analysis of waters, fertilizers, plants and soils. Scientific Publishers (India). 258p.

Stevenson, F.J. 1965. Gross chemical fractionation of organic matter. *In*: Methods of Soil Analysis. Part II. C. A., Black, D. D. Evans, J. L. White, L. E. Ensminger and F. E. Clark. (eds.). American Society of Agronomy, Madison, Wisconsin. pp.1409-1421.

Stevenson, F. J. 1991. Organic matter-Micronutrients Reactions in Soils. *In*: Micronutrients in agriculture. J. J. Mortverdt, F. R. Cox, L. M. Shuman. R. M. Welch (eds.) Madison. SSSA. pp.145-186.

Sunita, M. and Uma, M. 1993. Soil conditions as affected by various age groups of Eucalypts and Populus plantations in Tarai region of U.P. Proceedings of the Indian National Science Academy. Part B, Biological Sciences. 59: 67-70.

*Suwannaratana, S. 1999. Comparison of teak and pine plantations in northern Thailand. Saarbrucken, Germany: Universitat des Saarlandes. xv + 135.

Thiyageshwari, Subramanium, Duraisamy, Selvi and Sundararajan, Amutha. 2006. Micronutrient status in a dry deciduous tropical forest of the scrub jungle of mettupalayam, Coimbatore, India. 18Th World Congress of Soil Science. July 9-15, 2006-Philadelphia, Pennsylvania, USA.

Tiarks, A., Nambiar, E. K. S. and Cossalter. C. 1998. Site Management and Productivity in Tropical Forest Plantations. Occasional paper No. 16ISSN 0854-9818, CIFOR

Trevor, H., Booth, and Nambiar, E. K. S. 2001. Sustainable plantation forestry in the tropics: New opportunities and collaborative research. *In*: Proceedings of the international symposium, Tropical forestry research challenges in the millennium. R.V. Varma, K.V. Bhat, E. M. Muralidharan and J. K. Sharma (eds.). Kerala Forest Research Institute. Peechi, India. pp: 77-90.

Varghese, M., Nicodemus, A., Hegde, R. and Subamanian, K. 2001. Status of genetic impovement of eucalypts in India. *In:* Proceedings of the international symposium, Tropical forestry research challenges in the millennium. R.V. Varma, K.V. Bhat, E. M. Muralidharan, J. K. Sharma (eds.) Kerala Forest Research Institute. Peechi, India. pp: 159-164.

Waksman, S. A. and Hutchings, I. J. 1935. Chemical nature of soil organic matter in different soil types. *Soil Science*, 40: 347-363.

Wang, T. S. C. 1967. Soil organic compounds as plant growth promoters and inhibitors. *Soils and fertilizers in Taiwan*, pp. 1-13.

Watanabe, P. S. and Olsen, S. R. 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extract from plant. *Proceedings of Soil Science America*, 29: 677-678.

White, Jeffrey, G. and Zasoski, Robert, J. 1999. Mapping soil micronutrients. *Field Crops Research*, 60: 11-26.

Xu DaPing. and Dell, BerNie. 2002. Nutrient management for eucalypt plantations in south China. *Chinese Forestry Science and Technology*, 1: 29-41.

Zakaria, I. and Lokmal, N. 1998. Teak in Malaysia. *In*: Teak for the Future - Proceedings of the Second Regional Seminar on Teak. 29 May- June 3, 1995. Kashio, M and White, K. (eds.). Yagon. Myanmar. FAO. Regional office for Asia and Pacific Bangkok. 249p.

*not referred to in the original

Appendices

Appendix 1

ANOVA of physical properties in 0-60cm depth for comparing between natural forest and teak plantations of location I

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Groups	1	303.565	303.565	18.934**
	Within Groups	15	240.492	16.033	
	Total	16	544.057		
S	Between Groups	1	0.105	0.105	0.002
	Within Groups	15	830.235	55.349	
	Total	16	830.340		
Si	Between Groups	1	74.773	74.773	4.257
	Within Groups	15	263.492	17.566	
	Total	16	338.265		
Cly	Between Groups	1	73.604	73.604	1.430
	Within Groups	15	771.922	51.461	
	Total	16	845.526		
BD	Between Groups	1	0.02750	0.02750	7.765*
	Within Groups	15	0.05313	0.003542	
	Total	16	0.08064		
PD	Between Groups	1	0.03328	0.03328	9.872**
	Within Groups	15	0.05057	0.003371	
	Total	16	0.08386		
PS	Between Groups	1	11.295	11.295	2.308
	Within Groups	15	73.406	4.894	
	Total	16	84.701		
WHC	Between Groups	1	139.576	139.576	12.339**
	Within Groups	15	169.674	11.312	
	Total	16	309.251		

Appendix 2

ANOVA of physical properties in 0-20cm depth for comparing between natural forest and teak plantations of location I

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Groups	1	221.341	221.341	20.756**
	Within Groups	15	159.957	10.664	
	Total	16	381.298		
S	Between Groups	1	19.769	19.769	0.298
	Within Groups	15	994.467	66.298	
	Total	16	1014.235		
Si	Between Groups	1	86.188	86.188	3.936
	Within Groups	15	328.429	21.895	
	Total	16	414.618		
Cly	Between Groups	1	216.569	216.569	3.466
	Within Groups	15	937.167	62.478	
	Total	16	1153.735		
BD	Between Groups	1	0.080	0.080	17.980**
	Within Groups	15	0.067	0.004	
	Total	16	0.146		
PD	Between Groups	1	0.042	0.042	13.758**
	Within Groups	15	0.046	0.003	
	Total	16	0.088		
PS	Between Groups	1	60.315	60.315	10.265**
	Within Groups	15	88.136	5.876	
	Total	16	148.451		
WHC	Between Groups	1	288.695	288.695	39.413**
	Within Groups	15	109.874	7.325	
	Total	16	398.569		

Appendix 3

ANOVA of physical properties in 20-40cm depth for comparing between natural forest and teak plantations of location I

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Groups	1	574.800	574.800	14.543**
	Within Groups	15	592.877	39.525	
	Total	16	1167.678		
S	Between Groups	1	42.009	42.009	.687
	Within Groups	15	917.050	61.137	
	Total	16	959.059		
Si	Between Groups	1	335.515	335.515	4.549
	Within Groups	15	1106.250	73.750	
	Total	16	1441.765		
Cly	Between Groups	1	143.813	143.813	2.276
	Within Groups	15	947.717	63.181	
	Total	16	1091.529		
BD	Between Groups	1	0.039	0.039	5.808*
	Within Groups	15	0.101	0.007	
	Total	16	0.139		
PD	Between Groups	1	0.010	0.010	1.806
	Within Groups	15	0.079	0.005	
	Total	16	0.089		
PS	Between Groups	1	37.320	37.320	4.092
	Within Groups	15	136.796	9.120	
	Total	16	174.116		
WHC	Between Groups	1	86.829	86.829	4.261
	Within Groups	15	305.631	20.375	
	Total	16	392.460		

Appendix 4

ANOVA of physical properties in 40-60cm depth for comparing between natural forest and teak plantations of location I

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Groups	1	180.012	180.012	3.903
	Within Groups	15	691.804	46.120	
	Total	16	871.816		
S	Between Groups	1	1.133	1.133	0.011
	Within Groups	15	1486.867	99.124	
	Total	16	1488.000		
Si	Between Groups	1	2.754	2.754	0.130
	Within Groups	15	317.717	21.181	
	Total	16	320.471		
Cly	Between Groups	1	0.942	0.942	0.011
	Within Groups	15	1320.117	88.008	
	Total	16	1321.059		
BD	Between Groups	1	0.000	0.000	0.063
	Within Groups	15	0.076	0.005	
	Total	16	0.076		
PD	Between Groups	1	0.060	0.060	11.733**
	Within Groups	15	0.077	0.005	
	Total	16	0.137		
PS	Between Groups	1	14.387	14.387	1.882
	Within Groups	15	114.692	7.646	
	Total	16	129.079		
WHC	Between Groups	1	83.420	83.420	3.602
	Within Groups	15	347.417	23.161	
	Total	16	430.838		

Appendix 5

ANOVA of physical properties in 0-60cm depth for comparing between natural forest and teak plantations of location II

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Groups	1	78.160	78.160	2.256
	Within Groups	17	588.915	34.642	
	Total	18	667.075		
S	Between Groups	1	1171.059	1171.059	65.908**
	Within Groups	17	302.056	17.768	
	Total	18	1473.114		
Si	Between Groups	1	226.580	226.580	12.072**
	Within Groups	17	319.082	18.770	
	Total	18	545.662		
Cly	Between Groups	1	367.418	367.418	12.170**
	Within Groups	17	513.230	30.190	
	Total	18	880.648		
BD	Between Groups	1	0.0053403	0.00534	3.405
	Within Groups	17	0.02666	0.001568	
	Total	18	0.03200		
PD	Between Groups	1	0.02167	0.02167	14.397**
	Within Groups	17	0.02559	0.001505	
	Total	18	0.04725		
PS	Between Groups	1	0.004456	0.004456	.002
	Within Groups	17	48.402	2.847	
	Total	18	48.406		
WHC	Between Groups	1	29.024	29.024	4.536*
	Within Groups	17	108.787	6.399	
	Total	18	137.811		

Appendix 6

ANOVA of physical properties in 0-20cm depth for comparing between natural forest and teak plantations of location II

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Groups	1	55.525	55.525	8.944**
	Within Groups	17	105.538	6.208	
	Total	18	161.063		
S	Between Groups	1	1196.781	1196.781	200.973**
	Within Groups	17	101.234	5.955	
	Total	18	1298.015		
Si	Between Groups	1	141.749	141.749	8.492*
	Within Groups	17	283.766	16.692	
	Total	18	425.514		
Cly	Between Groups	1	514.777	514.777	22.633**
	Within Groups	17	386.653	22.744	
	Total	18	901.430		
BD	Between Groups	1	0.017	0.017	6.573*
	Within Groups	17	0.043	0.003	
	Total	18	0.060		
PD	Between Groups	1	0.029	0.029	15.901**
	Within Groups	17	0.031	0.002	
	Total	18	0.061		
PS	Between Groups	1	1.210	1.210	0.375
	Within Groups	17	54.884	3.228	
	Total	18	56.095		
WHC	Between Groups	1	157.738	157.738	13.030**
	Within Groups	17	205.801	12.106	
	Total	18	363.539		

Appendix 7

ANOVA of physical properties in 20-40cm depth for comparing between natural forest and teak plantations of location II

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Groups	1	41.699	41.699	0.856
	Within Groups	17	828.432	48.731	
	Total	18	870.132		
S	Between Groups	1	1172.267	1172.267	45.265**
	Within Groups	17	440.267	25.898	
	Total	18	1612.534		
Si	Between Groups	1	261.205	261.205	9.100**
	Within Groups	17	487.986	28.705	
	Total	18	749.191		
Cly	Between Groups	1	326.761	326.761	7.772*
	Within Groups	17	714.745	42.044	
	Total	18	1041.506		
BD	Between Groups	1	0.004	0.004	1.323
	Within Groups	17	0.048	0.003	
	Total	18	0.052		
PD	Between Groups	1	0.020	0.020	7.681*
	Within Groups	17	0.043	0.003	
	Total	18	0.063		
PS	Between Groups	1	0.018	0.018	0.002
	Within Groups	17	125.256	7.368	
	Total	18	125.273		
WHC	Between Groups	1	11.294	11.294	1.468
	Within Groups	17	130.772	7.692	
	Total	18	142.066		

Appendix 8

ANOVA of physical properties in 40-60cm depth for comparing between natural forest and teak plantations of location II

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Groups	1	159.098	159.098	1.246
	Within Groups	17	2171.429	127.731	
	Total	18	2330.526		
S	Between Groups	1	1144.421	1144.421	22.263**
	Within Groups	17	873.893	51.405	
	Total	18	2018.315		
Si	Between Groups	1	292.070	292.070	10.405**
	Within Groups	17	477.186	28.070	
	Total	18	769.256		
Cly	Between Groups	1	280.203	280.203	6.473*
	Within Groups	17	735.948	43.291	
	Total	18	1016.151		
BD	Between Groups	1	0.001	0.001	0.673
	Within Groups	17	0.021	0.001	
	Total	18	0.022		
PD	Between Groups	1	0.017	0.017	2.134
	Within Groups	17	0.136	0.008	
	Total	18	0.153		
PS	Between Groups	1	1.067	1.067	0.281
	Within Groups	17	64.492	3.794	
	Total	18	65.559		
WHC	Between Groups	1	0.059	.059	.005
	Within Groups	17	207.821	12.225	
	Total	18	207.880		

Appendix 9

ANOVA of physical properties in 0-60cm depth for comparing between natural forest and eucalypts plantations

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Groups	1	78.562	78.562	11.539**
	Within Groups	18	122.554	6.809	
	Total	19	201.117		
S	Between Groups	1	186.091	186.091	9.684**
	Within Groups	18	345.881	19.216	
	Total	19	531.972		
Si	Between Groups	1	2.963E-02	2.963E-02	.011
	Within Groups	18	46.993	2.611	
	Total	19	47.022		
Cly	Between Groups	1	183.750	183.750	15.874**
	Within Groups	18	208.356	11.575	
	Total	19	392.106		
BD	Between Groups	1	4.612E-02	4.612E-02	18.378**
	Within Groups	18	4.517E-02	2.509E-03	
	Total	19	9.128E-02		
PD	Between Groups	1	2.150E-02	2.150E-02	1.970
	Within Groups	18	.196	1.091E-02	
	Total	19	.218		
PS	Between Groups	1	26.622	26.622	12.944**
	Within Groups	18	37.020	2.057	
	Total	19	63.642		
WHC	Between Groups	1	60.400	60.400	19.988**
	Within Groups	18	54.393	3.022	
	Total	19	114.792		

Appendix 10

ANOVA of physical properties in 0-20cm depth for comparing between natural forest and eucalypts plantations

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Groups	1	427.200	427.200	34.649**
	Within Groups	18	221.929	12.329	
	Total	19	649.130		
S	Between Groups	1	308.267	308.267	13.451**
	Within Groups	18	412.533	22.919	
	Total	19	720.800		
Si	Between Groups	1	2.817	2.817	0.437
	Within Groups	18	116.133	6.452	
	Total	19	118.950		
Cly	Between Groups	1	252.150	252.150	24.829**
	Within Groups	18	182.800	10.156	
	Total	19	434.950		
BD	Between Groups	1	0.078	0.078	15.569**
	Within Groups	18	0.090	0.005	
	Total	19	0.168		
PD	Between Groups	1	0.002	0.002	0.120
	Within Groups	18	0.328	0.018	
	Total	19	0.330		
PS	Between Groups	1	117.544	117.544	29.176**
	Within Groups	18	72.519	4.029	
	Total	19	190.063		
WHC	Between Groups	1	85.670	85.670	9.235**
	Within Groups	18	166.982	9.277	
	Total	19	252.651		

Appendix 11

ANOVA of physical properties in 20-40cm depth for comparing between natural forest and eucalypts plantations

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Groups	1	73.926	73.926	3.578
	Within Groups	18	371.864	20.659	
	Total	19	445.790		
S	Between Groups	1	141.067	141.067	7.294*
	Within Groups	18	348.133	19.341	
	Total	19	489.200		
Si	Between Groups	1	5.400	5.400	1.929
	Within Groups	18	50.400	2.800	
	Total	19	55.800		
Cly	Between Groups	1	209.067	209.067	17.126**
	Within Groups	18	219.733	12.207	
	Total	19	428.800		
BD	Between Groups	1	0.063	0.063	11.214**
	Within Groups	18	0.101	0.006	
	Total	19	0.164		
PD	Between Groups	1	0.207	0.207	10.519**
	Within Groups	18	0.355	0.020	
	Total	19	0.562		
PS	Between Groups	1	1.880	1.880	0.667
	Within Groups	18	50.703	2.817	
	Total	19	52.583		
WHC	Between Groups	1	84.645	84.645	11.742**
	Within Groups	18	129.763	7.209	
	Total	19	214.408		

Appendix 12

ANOVA of physical properties in 40-60cm depth for comparing between natural forest and eucalypts plantations

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Groups	1	7.162	7.162	0.363
	Within Groups	18	355.244	19.736	
	Total	19	362.406		
S	Between Groups	1	132.017	132.017	5.732*
	Within Groups	18	414.533	23.030	
	Total	19	546.550		
Si	Between Groups	1	1.350	1.350	0.769
	Within Groups	18	31.600	1.756	
	Total	19	32.950		
Cly	Between Groups	1	106.667	106.667	5.638*
	Within Groups	18	340.533	18.919	
	Total	19	447.200		
BD	Between Groups	1	0.013	0.013	6.651*
	Within Groups	18	0.035	0.002	
	Total	19	0.048		
PD	Between Groups	1	0.004	0.004	0.187
	Within Groups	18	0.369	0.021	
	Total	19	0.373		
PS	Between Groups	1	10.668	10.668	3.428
	Within Groups	18	56.012	3.112	
	Total	19	66.680		
WHC	Between Groups	1	23.611	23.611	2.096
	Within Groups	18	202.793	11.266	
	Total	19	226.403		

Appendix 13

ANOVA of physical properties in 0-60cm depth between natural forest and teak plantations of different age class in location I

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Age groups	2	366.631	183.315	14.465**
	Error	14	177.426	12.673	
	Total	16	544.057		
S	Between Age groups	2	0.105	5.247E-02	.001
	Error	14	830.235	59.302	
	Total	16	830.340		
Si	Between Age groups	2	145.074	72.537	5.257*
	Error	14	193.190	13.799	
	Total	16	338.265		
Cly	Between Age groups	2	152.471	76.235	1.540
	Error	14	693.056	49.504	
	Total	16	845.526		
BD	Between Age groups	2	0.02894	0.01447	3.919*
	Error	14	0.05170	0.003693	
	Total	16	0.08064		
PD	Between Age groups	2	0.04848	0.02424	9.595**
	Error	14	0.03537	0.02527	
	Total	16	0.08386		
PS	Between Age groups	2	11.732	5.866	1.125
	Error	14	72.969	5.212	
	Total	16	84.701		
WHC	Between Age groups	2	158.989	79.495	7.407**
	Error	14	150.261	10.733	
	Total	16	309.251		

Appendix 14

ANOVA of physical properties in 0-20cm depth between natural forest and teak plantations of different age class in location I

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Age groups	2	221.435	110.717	9.696**
	Error	14	159.863	11.419	
	Total	16	381.298		
S	Between Age groups	2	21.635	10.818	.153
	Error	14	992.600	70.900	
	Total	16	1014.235		
Si	Between Age groups	2	86.218	43.109	1.838
	Error	14	328.400	23.457	
	Total	16	414.618		
Cly	Between Age groups	2	217.035	108.518	1.622
	Error	14	936.700	66.907	
	Total	16	1153.735		
BD	Between Age groups	2	0.088	0.044	10.460**
	Error	14	0.059	0.004	
	Total	16	0.146		
PD	Between Age groups	2	0.054	0.027	11.402**
	Error	14	0.033	0.002	
	Total	16	0.088		
PS	Between Age groups	2	62.510	31.255	5.092*
	Error	14	85.941	6.139	
	Total	16	148.451		
WHC	Between Age groups	2	312.007	156.004	25.231**
	Error	14	86.562	6.183	
	Total	16	398.569		

Appendix 15

ANOVA of physical properties in 20-40cm depth between natural forest and teak plantations of different age class in location I

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Age groups	2	635.373	317.686	8.355**
	Error	14	532.305	38.022	
	Total	16	1167.678		
S	Between Age groups	2	57.630	28.815	.448
	Error	14	901.429	64.388	
	Total	16	959.059		
Si	Between Age groups	2	863.708	431.854	10.459**
	Error	14	578.057	41.290	
	Total	16	1441.765		
Cly	Between Age groups	2	519.072	259.536	6.347*
	Error	14	572.457	40.890	
	Total	16	1091.529		
BD	Between Age groups	2	0.048	0.024	3.704
	Error	14	0.091	0.007	
	Total	16	0.139		
PD	Between Age groups	2	0.035	0.017	4.454*
	Error	14	0.054	0.004	
	Total	16	0.089		
PS	Between Age groups	2	38.492	19.246	1.987
	Error	14	135.623	9.687	
	Total	16	174.116		
WHC	Between Age groups	2	87.427	43.713	2.006
	Error	14	305.034	21.788	
	Total	16	392.460		

Appendix 16

ANOVA of physical properties in 40-60cm depth between natural forest and teak plantations of different age class in location I

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Age groups	2	427.585	213.792	6.738**
	Error	14	444.232	31.731	
	Total	16	871.816		
S	Between Age groups	2	29.943	14.971	.144
	Error	14	1458.057	104.147	
	Total	16	1488.000		
Si	Between Age groups	2	6.756	3.378	.151
	Error	14	313.714	22.408	
	Total	16	320.471		
Cly	Between Age groups	2	64.202	32.101	.358
	Error	14	1256.857	89.776	
	Total	16	1321.059		
BD	Between Age groups	2	0.005	0.003	.539
	Error	14	0.071	0.005	
	Total	16	0.076		
PD	Between Age groups	2	0.070	0.035	7.370**
	Error	14	0.067	0.005	
	Total	16	0.137		
PS	Between Age groups	2	35.082	17.541	2.613
	Error	14	93.997	6.714	
	Total	16	129.079		
WHC	Between Age groups	2	141.438	70.719	3.421
	Error	14	289.400	20.671	
	Total	16	430.838		

Appendix 17

ANOVA of physical properties in 0-60cm depth between natural forest and teak plantations of different age class in location II

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Age groups	2	103.433	51.717	1.468
	Error	16	563.642	35.228	
	Total	18	667.075		
S	Between Age groups	2	1182.753	591.376	32.587**
	Error	16	290.361	18.148	
	Total	18	1473.114		
Si	Between Age groups	2	236.994	118.497	6.142*
	Error	16	308.668	19.292	
	Total	18	545.662		
Cly	Between Age groups	2	367.455	183.728	5.728*
	Error	16	513.193	32.075	
	Total	18	880.648		
BD	Between Age groups	2	0.005678	0.002839	1.726
	Error	16	0.02632	0.001645	
	Total	18	0.03200		
PD	Between Age groups	2	0.02448	0.01224	8.601**
	Error	16	0.02277	0.01423	
	Total	18	0.04725		
PS	Between Age groups	2	1.989	0.995	.343
	Error	16	46.417	2.901	
	Total	18	48.406		
WHC	Between Age groups	2	29.058	14.529	2.138
	Error	16	108.753	6.797	
	Total	18	137.811		

Appendix 18

ANOVA of physical properties in 0-20cm depth between natural forest and teak plantations of different age class in location II

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Age groups	2	57.692	28.846	4.465*
	Error	16	103.371	6.461	
	Total	18	161.063		
S	Between Age groups	2	1198.458	599.229	96.303**
	Error	16	99.557	6.222	
	Total	18	1298.015		
Si	Between Age groups	2	149.526	74.763	4.334*
	Error	16	275.988	17.249	
	Total	18	425.514		
Cly	Between Age groups	2	517.009	258.505	10.759**
	Error	16	384.420	24.026	
	Total	18	901.430		
BD	Between Age groups	2	0.017	0.008	3.109
	Error	16	0.043	0.003	
	Total	18	0.060		
PD	Between Age groups	2	0.031	0.015	8.300**
	Error	16	0.030	0.002	
	Total	18	0.061		
PS	Between Age groups	2	1.351	0.675	.197
	Error	16	54.744	3.421	
	Total	18	56.095		
WHC	Between Age groups	2	160.769	80.385	6.343**
	Error	16	202.770	12.673	
	Total	18	363.539		

Appendix 19

ANOVA of physical properties in 20-40cm depth between natural forest and teak plantations of different age class in location II.

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Age groups	2	110.043	55.021	1.158
	Error	16	760.089	47.506	
	Total	18	870.132		
S	Between Age groups	2	1184.559	592.279	22.143**
	Error	16	427.975	26.748	
	Total	18	1612.534		
Si	Between Age groups	2	270.616	135.308	4.524*
	Error	16	478.575	29.911	
	Total	18	749.191		
Cly	Between Age groups	2	326.953	163.476	3.661*
	Error	16	714.553	44.660	
	Total	18	1041.506		
BD	Between Age groups	2	0.004	0.002	.623
	Error	16	0.048	0.003	
	Total	18	0.052		
PD	Between Age groups	2	0.027	0.013	6.012*
	Error	16	0.036	0.002	
	Total	18	0.063		
PS	Between Age groups	2	2.083	1.041	.135
	Error	16	123.191	7.699	
	Total	18	125.273		
WHC	Between Age groups	2	13.654	6.827	.851
	Error	16	128.411	8.026	
	Total	18	142.066		

Appendix 20

ANOVA of physical properties in 40-60cm depth between natural forest and teak plantations of different age class in location II

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Age groups	2	227.771	113.885	.867
	Error	16	2102.756	131.422	
	Total	18	2330.526		
S	Between Age groups	2	1174.213	587.107	11.129**
	Error	16	844.101	52.756	
	Total	18	2018.315		
Si	Between Age groups	2	306.698	153.349	5.304*
	Error	16	462.558	28.910	
	Total	18	769.256		
Cly	Between Age groups	2	282.871	141.435	3.086
	Error	16	733.280	45.830	
	Total	18	1016.151		
BD	Between Age groups	2	0.003	0.002	1.316
	Error	16	0.019	0.001	
	Total	18	0.022		
PD	Between Age groups	2	0.018	0.009	1.079
	Error	16	0.135	0.008	
	Total	18	0.153		
PS	Between Age groups	2	6.898	3.449	.941
	Error	16	58.662	3.666	
	Total	18	65.559		
WHC	Between Age groups	2	14.739	7.370	.610
	Error	16	193.141	12.071	
	Total	18	207.880		

Appendix 21

ANOVA of physical properties in 0-60cm depth between natural forest and eucalypt plantations of different rotations

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Age groups	3	94.679	31.560	4.744*
	Error	16	106.438	6.652	
	Total	19	201.117		
S	Between Age groups	3	306.506	102.169	7.250**
	Error	16	225.467	14.092	
	Total	19	531.972		
Si	Between Age groups	3	21.778	7.259	4.601*
	Error	16	25.244	1.578	
	Total	19	47.022		
Cly	Between Age groups	3	224.283	74.761	7.128**
	Error	16	167.822	10.489	
	Total	19	392.106		
BD	Between Age groups	3	0.05689	0.01896	8.822**
	Error	16	0.03439	0.002149	
	Total	19	0.09128		
PD	Between Age groups	3	.121	0.04041	6.687**
	Error	16	0.09671	0.006044	
	Total	19	.218		
PS	Between Age groups	3	27.984	9.328	4.186*
	Error	16	35.658	2.229	
	Total	19	63.642		
WHC	Between Age groups	3	74.781	24.927	9.968**
	Error	16	40.011	2.501	
	Total	19	114.792		

Appendix 22

ANOVA of physical properties in 0-20cm depth between natural forest and eucalypt plantations of different rotations

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Age groups	3	487.265	162.422	16.055**
	Error	16	161.864	10.117	
	Total	19	649.129		
S	Between Age groups	3	461.200	153.733	9.475**
	Error	16	259.600	16.225	
	Total	19	720.800		
Si	Between Age groups	3	57.750	19.250	5.033*
	Error	16	61.200	3.825	
	Total	19	118.950		
Cly	Between Age groups	3	283.750	94.583	10.009**
	Error	16	151.200	9.450	
	Total	19	434.950		
BD	Between Age groups	3	0.084	0.028	5.371**
	Error	16	0.084	0.005	
	Total	19	0.168		
PD	Between Age groups	3	0.040	0.013	.729
	Error	16	0.290	0.018	
	Total	19	0.330		
PS	Between Age groups	3	117.734	39.245	8.681**
	Error	16	72.329	4.521	
	Total	19	190.063		
WHC	Between Age groups	3	128.986	42.995	5.563**
	Error	16	123.666	7.729	
	Total	19	252.651		

Appendix 23

ANOVA of physical properties in 20-40cm depth between natural forest and eucalypt plantations of different rotations

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Age groups	3	154.290	51.430	2.823
	Error	16	291.500	18.219	
	Total	19	445.790		
S	Between Age groups	3	219.600	73.200	4.344*
	Error	16	269.600	16.850	
	Total	19	489.200		
Si	Between Age groups	3	25.000	8.333	4.329*
	Error	16	30.800	1.925	
	Total	19	55.800		
Cly	Between Age groups	3	228.800	76.267	6.101**
	Error	16	200.000	12.500	
	Total	19	428.800		
BD	Between Age groups	3	0.105	0.035	9.400**
	Error	16	0.059	0.004	
	Total	19	0.164		
PD	Between Age groups	3	0.374	0.125	10.656**
	Error	16	0.187	0.012	
	Total	19	0.562		
PS	Between Age groups	3	11.335	3.778	1.466
	Error	16	41.248	2.578	
	Total	19	52.583		
WHC	Between Age groups	3	95.260	31.753	4.264*
	Error	16	119.148	7.447	
	Total	19	214.408		

Appendix 24

ANOVA of physical properties in 40-60cm depth between natural forest and eucalypt plantations of different rotations

Variables	Source	df	Sum of Squares	Mean Square	F
G	Between Age groups	3	34.030	11.343	.553
	Error	16	328.376	20.524	
	Total	19	362.406		
S	Between Age groups	3	272.950	90.983	5.321*
	Error	16	273.600	17.100	
	Total	19	546.550		
Si	Between Age groups	3	8.950	2.983	1.989
	Error	16	24.000	1.500	
	Total	19	32.950		
Cly	Between Age groups	3	191.600	63.867	3.998*
	Error	16	255.600	15.975	
	Total	19	447.200		
BD	Between Age groups	3	0.015	0.005	2.293
	Error	16	0.034	0.002	
	Total	19	0.048		
PD	Between Age groups	3	0.132	0.044	2.911
	Error	16	0.241	0.015	
	Total	19	0.373		
PS	Between Age groups	3	11.296	3.765	1.088
	Error	16	55.384	3.462	
	Total	19	66.680		
WHC	Between Age groups	3	36.641	12.214	1.030
	Error	16	189.762	11.860	
	Total	19	226.403		

Appendix 25

Mean of physical properties in Location 1

0-20cm

Age class	G	S	Si	Cly	BD	PD	PS	WHC
NF	4.9^{b}	66	7	27	1.02^{b}	2.39^{c}	57.3^{a}	53.4^{a}
21-30 TP	12.9^{a}	68	12	20	1.14^{a}	2.46^{b}	53.7^{b}	46.0^{b}
31-40 TP	12.8^{a}	69	12	19	1.19^{a}	2.52^{a}	52.8^{b}	43.1^{b}

20-40cm

Age class	G	S	Si	Cly	BD	PD	PS	WHC
NF	5.3^{b}	67	5^{b}	28^{a}	1.05^{a}	2.42^{b}	56.7	50.7
21-30 TP	20.7^{a}	62	23^{a}	15^{b}	1.12^{ab}	2.43^{b}	53.8	46.0
31-40 TP	16.1^{a}	65	9^{b}	26^{a}	1.18^{b}	2.52^{a}	53.2	45.6

40-60cm

Age class	G	S	Si	Cly	BD	PD	PS	WHC
NF	11.5^{b}	63	12	25	1.12^{a}	2.39^{b}	53.4	49.7
21-30 TP	24.1	65	12	23	1.15^{b}	2.49^{a}	53.8	47.5
31-40 TP	14.8^{b}	62	10	28	1.11^{b}	2.55^{a}	56.5	43.0

0-60cm

Age class	G	S	Si	Cly	BD	PD	PS	WHC
NF	7.2^{a}	65	8^{a}	27	1.06^{a}	2.40^{a}	55.8	51.3^{a}
21-30 TP	19.2^{b}	65	15^{b}	19	1.14^{a}	2.47^{a}	53.8	46.5^{b}
31-40 TP	14.6^{c}	65	11^{a}	24	1.16^{b}	2.53^{b}	54.2	43.9^{b}

Mean of physical properties in Location 2

0-20cm

Age class	G	S	Si	Cly	BD	PD	PS	WHC
NF	7.3^{b}	61^{b}	18^{a}	21^{a}	0.98^{a}	2.34^{b}	58.0	53.7^{a}
41-50 TP	11.7^{a}	79^{a}	11^{b}	10^{b}	1.05^{b}	2.42^{a}	57.3	47.8^{b}
>50 TP	10.9^{a}	78^{a}	12^{b}	9^{b}	1.04^{b}	2.44^{a}	57.5	46.8^{b}

20-40cm

Age class	G	S	Si	Cly	BD	PD	PS	WHC
NF	13.6	58^{b}	21^{a}	21^{a}	1.00	2.34^{a}	56.9	49.4
41-50 TP	14.0	78^{a}	11^{b}	11^{b}	1.04	2.38^{a}	56.3	48.2
>50 TP	18.6	75^{a}	13^{b}	11^{b}	1.04	2.43^{b}	57.1	47.4

40-60cm

Age class	G	S	Si	Cly	BD	PD	PS	WHC
NF	14.0	58.^{b}	21^{a}	21^{a}	1.02	2.35	56.6	49.3
41-50 TP	17.6	78^{a}	11^{b}	11^{b}	1.05	2.41	56.3	47.8
>50 TP	22.2	75^{a}	13^{b}	12^{b}	1.02	2.43	57.7	49.9

0-60cm

Age class	G	S	Si	Cly	BD	PD	PS	WHC
NF	11.6	59^{a}	20^{a}	21^{a}	1.00	2.34^{a}	57.2	50.8
41-50 TP	14.4	78^{b}	11^{b}	11^{b}	1.05	2.40^{b}	56.6	47.8
≥50 TP	17.2	76^{b}	13^{b}	11^{b}	1.04	2.43^{b}	57.4	48.0

Mean of physical properties in Location 3

0-20cm

Age class	G	S	Si	Cly	BD	PD	PS	WHC
N.F	5.9^{c}	75^{c}	9^{ab}	16^{a}	0.97^{b}	2.34	58.4^{a}	55.7^{a}
E II	14.1^{b}	87^{a}	7^{b}	6^{b}	1.14^{a}	2.42	52.9^{b}	48.6^{c}
E III C	19.1^{a}	80^{c}	11^{a}	9^{b}	1.12^{a}	2.37	52.7^{b}	51.6^{bc}
E III R	16.5^{ab}	84^{ab}	7^{b}	9^{b}	1.09^{a}	2.30	52.7^{b}	52.7^{ab}

20-40cm

Age class	G	S	Si	Cly	BD	PD	PS	WHC
N.F	15.8^{a}	75^{c}	8^{b}	17^{a}	1.04^{c}	2.18^{ba}	52.3	52.4^{a}
E II	23.3^{b}	84^{a}	8^{b}	8^{b}	1.23^{a}	2.56^{b}	51.9	46.8^{b}
E III C	19.7^{ab}	78^{bc}	11^{a}	11^{b}	1.18^{ab}	2.37^{a}	50.5	48.8^{ab}
E III R	17.8^{ab}	81^{ab}	9^{ab}	10^{b}	1.10^{bc}	2.31^{a}	52.4	47.4^{b}

40-60cm

Age class	G	S	Si	Cly	BD	PD	PS	WHC
N.F	23.2	74^{b}	10	16^{a}	1.18^{a}	2.47^{ab}	52.3	51.1
E II	23.2	84^{a}	8	7^{b}	1.25^{b}	2.55^{a}	50.9	47.6
E III C	22.3	77^{b}	10	13^{a}	1.23^{ab}	2.44^{ab}	50.5	48.1
E III R	20.0	79^{ab}	9	11^{ab}	1.23^{ab}	2.33^{b}	50.4	49.8

0-60cm

Age class	G	S	Si	Cly	BD	PD	PS	WHC
N.F	15^{a}	75^{a}	9^{b}	16^{a}	1.06^{a}	2.33^{a}	54.3^{a}	53.1^{a}
E II	20.2^{b}	85^{b}	8^{b}	7^{b}	1. 21^{b}	2.51^{b}	51.9^{b}	47.7^{b}
E III C	20.4^{b}	78^{c}	11^{a}	11^{b}	1.18^{bc}	2.40^{a}	51.3^{b}	49.5^{bc}
E III R	18.1^{ba}	81^{bc}	9^{b}	10^{b}	1.14^{c}	2.31^{a}	51.8^{b}	49.9^{c}

Figures with different superscript differ significantly from each other.

NF –Natural forest, TP – Teak plantation,
EII – Eucalypt II^{nc} rotation, EIII C – Eucalypt IIIrd rotation coppiced, EIII R - Eucalypt IIIrd rotation replanted

Appendix 26

ANOVA of chemical properties in 0-60cm depth for comparing between natural forest and younger teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	1	3.932E-04	3.932E-04	.016
	Error	15	.362	2.416E-02	
	Total	16	.363		
Ex. Base	Between Age groups	1	1.621	1.621	.267
	Error	15	91.163	6.078	
	Total	16	92.784		
Ex. Na	Between Age groups	1	0.01057	0.01057	.102
	Error	15	1.559	0.104	
	Total	16	1.569		
Ex. K	Between Age groups	1	3.191	3.191	1.616
	Error	15	29.610	1.974	
	Total	16	32.801		
Ex. Ca	Between Age groups	1	8921.841	8921.841	3.182
	Error	15	42054.630	2803.642	
	Total	16	50976.471		
Ex. Mg	Between Age groups	1	990.221	990.221	1.140
	Error	15	13028.250	868.550	
	Total	16	14018.471		
Av. P	Between Age groups	1	0.02045	0.02045	.039
	Error	15	7.867	0.524	
	Total	16	7.887		
O.C	Between Age groups	1	2.881	2.881	45.748**
	Error	15	0.945	0.06298	
	Total	16	3.826		
Total. N	Between Age groups	1	38501.089	38501.089	.103
	Error	15	5629962.9	375330.864	
	Total	16	5668464.0		
C/N	Between Age groups	1	53.820	53.820	17.462**
	Error	15	46.233	3.082	
	Total	16	100.053		

Appendix 27

ANOVA of chemical properties in 0-20cm depth for comparing between natural forest and younger teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	1	0.014	0.014	0.405
	Error	15	0.525	0.035	
	Total	16	0.539		
Ex. Base	Between Age groups	1	1.07	1.07	.142
	Error	15	113.05	7.54	
	Total	16	114.12		
Ex. Na	Between Age groups	1	0.00	0.00	.001
	Error	15	2.61	0.17	
	Total	16	2.61		
Ex. K	Between Age groups	1	6.39	6.39	3.181
	Error	15	30.11	2.01	
	Total	16	36.50		
Ex. Ca	Between Age groups	1	20835.39	20835.39	3.511
	Error	15	89011.67	5934.11	
	Total	16	109847.06		
Ex. Mg	Between Age groups	1	894.14	894.14	.571
	Error	15	23494.92	1566.33	
	Total	16	24389.06		
Av. P	Between Age groups	1	1.81	1.81	.901
	Error	15	30.18	2.01	
	Total	16	32.00		
O.C	Between Age groups	1	4.84	4.84	45.800**
	Error	15	1.59	0.11	
	Total	16	6.42		
Total. N	Between Age groups	1	40156.86	40156.86	.073
	Error	15	8253666.7	550244.44	
	Total	16	8293823.5		
C/N	Between Age groups	1	44.98	44.98	24.082**
	Error	15	28.02	1.87	
	Total	16	73.00		

Appendix 28

ANOVA of chemical properties in 20-40cm depth for comparing between natural forest and younger teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	1	0.007	.007	.306
	Error	15	0.351	.023	
	Total	16	0.358		
Ex. Base	Between Age groups	1	9.04	9.04	1.339
	Error	15	101.20	6.75	
	Total	16	110.24		
Ex. Na	Between Age groups	1	0.00	0.00	.002
	Error	15	2.33	0.16	
	Total	16	2.33		
Ex. K	Between Age groups	1	1.17	1.17	.338
	Error	15	51.80	3.45	
	Total	16	52.96		
Ex. Ca	Between Age groups	1	1020.00	1020.00	.295
	Error	15	51780.00	3452.00	
	Total	16	52800.00		
Ex. Mg	Between Age groups	1	9482.45	9482.45	8.169*
	Error	15	17411.67	1160.78	
	Total	16	26894.12		
Av. P	Between Age groups	1	0.00	0.00	.000
	Error	15	4.19	0.28	
	Total	16	4.19		
O.C	Between Age groups	1	2.61	2.61	38.750**
	Error	15	1.01	0.07	
	Total	16	3.62		
Total. N	Between Age groups	1	574156.86	574156.86	.791
	Error	15	10884666.7	725644.44	
	Total	16	11458823.5		
C/N	Between Age groups	1	50.65	50.65	6.482*
	Error	15	117.22	7.81	
	Total	16	167.87		

Appendix 29

ANOVA of chemical properties in 40-60cm depth for comparing between natural forest and younger teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	1	0.021	.021	0.637
	Error	15	0.489	.033	
	Total	16	0.509		
Ex. Base	Between Age groups	1	3.41	3.41	.449
	Error	15	114.12	7.61	
	Total	16	117.53		
Ex. Na	Between Age groups	1	0.09	0.09	.580
	Error	15	2.44	0.16	
	Total	16	2.53		
Ex. K	Between Age groups	1	3.07	3.07	.804
	Error	15	57.23	3.82	
	Total	16	60.30		
Ex. Ca	Between Age groups	1	11467.06	11467.06	1.891
	Error	15	90980.00	6065.33	
	Total	16	102447.06		
Ex. Mg	Between Age groups	1	725.10	725.10	.438
	Error	15	24854.67	1656.98	
	Total	16	25579.77		
Av. P	Between Age groups	1	0.83	0.83	2.856
	Error	15	4.36	0.29	
	Total	16	5.19		
O.C	Between Age groups	1	1.63	1.63	24.253**
	Error	15	1.01	0.07	
	Total	16	2.64		
Total. N	Between Age groups	1	136509.80	136509.80	.276
	Error	15	7424666.7	494977.78	
	Total	16	7561176.5		
C/N	Between Age groups	1	66.99	66.99	17.745**
	Error	15	56.63	3.78	
	Total	16	123.62		

Appendix 29

ANOVA of chemical properties in 40-60cm depth for comparing between natural forest and younger teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	1	0.021	.021	0.637
	Error	15	0.489	.033	
	Total	16	0.509		
Ex. Base	Between Age groups	1	3.41	3.41	.449
	Error	15	114.12	7.61	
	Total	16	117.53		
Ex. Na	Between Age groups	1	0.09	0.09	.580
	Error	15	2.44	0.16	
	Total	16	2.53		
Ex. K	Between Age groups	1	3.07	3.07	.804
	Error	15	57.23	3.82	
	Total	16	60.30		
Ex. Ca	Between Age groups	1	11467.06	11467.06	1.891
	Error	15	90980.00	6065.33	
	Total	16	102447.06		
Ex. Mg	Between Age groups	1	725.10	725.10	.438
	Error	15	24854.67	1656.98	
	Total	16	25579.77		
Av. P	Between Age groups	1	0.83	0.83	2.856
	Error	15	4.36	0.29	
	Total	16	5.19		
O.C	Between Age groups	1	1.63	1.63	24.253**
	Error	15	1.01	0.07	
	Total	16	2.64		
Total. N	Between Age groups	1	136509.80	136509.80	.276
	Error	15	7424666.7	494977.78	
	Total	16	7561176.5		
C/N	Between Age groups	1	66.99	66.99	17.745**
	Error	15	56.63	3.78	
	Total	16	123.62		

Appendix 30

ANOVA of chemical properties in 0-60cm depth for comparing between natural forest and older teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	1	.533	.533	22.720**
	Error	17	.399	2.347E-02	
	Total	18	.932		
Ex. Base	Between Age groups	1	3.511	3.511	1.117
	Error	17	53.437	3.143	
	Total	18	56.947		
Ex. Na	Between Age groups	1	34.024	34.024	4.845*
	Error	17	119.382	7.022	
	Total	18	153.406		
Ex. K	Between Age groups	1	132.006	132.006	26.906**
	Error	17	83.405	4.906	
	Total	18	215.411		
Ex. Ca	Between Age groups	1	307.970	307.970	.102
	Error	17	51187.937	3011.055	
	Total	18	51495.906		
Ex. Mg	Between Age groups	1	3316.316	3316.316	5.159*
	Error	17	10927.032	642.767	
	Total	18	14243.348		
Av. P	Between Age groups	1	1.097	1.097	6.259*
	Error	17	2.980	0.175	
	Total	18	4.077		
O.C	Between Age groups	1	0.217	0.217	19.996**
	Error	17	0.184	0.01083	
	Total	18	0.401		
Total. N	Between Age groups	1	223895.51	223895.519	2.170
	Error	17	1753991.3	103175.962	
	Total	18	1977886.8		
C/N	Between Age groups	1	9.488	9.488	10.075**
	Error	17	16.010	.942	
	Total	18	25.499		

Appendix 31

ANOVA of chemical properties in 0-20cm depth for comparing between natural forest and older teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	1	0.556	0.556	16.870**
	Error	17	0.561	0.033	
	Total	18	1.117		
Ex. Base	Between Age groups	1	13.50	13.50	2.679
	Error	17	85.66	5.04	
	Total	18	99.16		
Ex. Na	Between Age groups	1	10.01	10.01	1.246
	Error	17	136.60	8.04	
	Total	18	146.61		
Ex. K	Between Age groups	1	33.09	33.09	5.598*
	Error	17	100.47	5.91	
	Total	18	133.56		
Ex. Ca	Between Age groups	1	3190.68	3190.68	1.464
	Error	17	37051.43	2179.50	
	Total	18	40242.11		
Ex. Mg	Between Age groups	1	1432.92	1432.92	1.603
	Error	17	15197.00	893.94	
	Total	18	16629.92		
Av. P	Between Age groups	1	0.03	0.03	.077
	Error	17	5.78	0.34	
	Total	18	5.81		
O.C	Between Age groups	1	0.92	0.92	66.252**
	Error	17	0.24	0.01	
	Total	18	1.15		
Total. N	Between Age groups	1	32395.56	32395.56	.129
	Error	17	4256490.8	250381.81	
	Total	18	4288886.3		
C/N	Between Age groups	1	5.09	5.09	1.442
	Error	17	59.95	3.53	
	Total	18	65.04		

Appendix 32

ANOVA of chemical properties in 20-40cm depth for comparing between natural forest and older teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	1	0.540	0.540	26.511**
	Error	17	0.346	0.020	
	Total	18	0.886		
Ex. Base	Between Age groups	1	0.72	0.72	.106
	Error	17	116.01	6.82	
	Total	18	116.74		
Ex. Na	Between Age groups	1	41.66	41.66	5.251*
	Error	17	134.88	7.93	
	Total	18	176.54		
Ex. K	Between Age groups	1	208.03	208.03	22.483**
	Error	17	157.29	9.25	
	Total	18	365.32		
Ex. Ca	Between Age groups	1	9001.20	9001.20	1.722
	Error	17	88851.43	5226.56	
	Total	18	97852.63		
Ex. Mg	Between Age groups	1	2800.68	2800.68	1.504
	Error	17	31649.43	1861.73	
	Total	18	34450.11		
Av. P	Between Age groups	1	0.79	0.79	6.570*
	Error	17	2.04	0.12	
	Total	18	2.83		
O.C	Between Age groups	1	0.11	0.11	3.412
	Error	17	0.57	0.03	
	Total	18	0.68		
Total. N	Between Age groups	1	159196.69	159196.69	1.147
	Error	17	2359788.9	138811.11	
	Total	18	2518985.6		
C/N	Between Age groups	1	6.29	6.29	8.973**
	Error	17	11.91	0.70	
	Total	18	18.19		

Appendix 33

ANOVA of chemical properties in 40-60cm depth for comparing between natural forest and older teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	1	0.504	0.504	7.502*
	Error	17	1.143	0.067	
	Total	18	1.647		
Ex. Base	Between Age groups	1	7.82	7.82	.735
	Error	17	180.91	10.64	
	Total	18	188.74		
Ex. Na	Between Age groups	1	62.10	62.10	4.816*
	Error	17	219.23	12.90	
	Total	18	281.33		
Ex. K	Between Age groups	1	204.29	204.29	32.755**
	Error	17	106.03	6.24	
	Total	18	310.31		
Ex. Ca	Between Age groups	1	203.31	203.31	.026
	Error	17	131291.43	7723.03	
	Total	18	131494.74		
Ex. Mg	Between Age groups	1	6721.88	6721.88	5.535*
	Error	17	20644.86	1214.40	
	Total	18	27366.74		
Av. P	Between Age groups	1	4.38	4.38	12.948**
	Error	17	5.75	0.34	
	Total	18	10.12		
O.C	Between Age groups	1	0.01	0.01	.292
	Error	17	0.59	0.03	
	Total	18	0.60		
Total. N	Between Age groups	1	706517.08	706517.08	2.745
	Error	17	4375203.7	257364.93	
	Total	18	5081720.8		
C/N	Between Age groups	1	20.06	20.06	7.285*
	Error	17	46.81	2.75	
	Total	18	66.87		

Appendix 34

ANOVA of chemical properties in 0-60cm depth for comparing between natural forest and eucalypts plantations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	1	2.249	2.249	68.572**
	Error	18	.590	3.280E-02	
	Total	19	2.839		
Ex. Base	Between Age groups	1	139.030	139.030	10.662**
	Error	18	234.726	13.040	
	Total	19	373.756		
Ex. Na	Between Age groups	1	1695.662	1695.662	6.240*
	Error	18	4891.691	271.761	
	Total	19	6587.353		
Ex. K	Between Age groups	1	49.021	49.021	1.491
	Error	18	591.852	32.881	
	Total	19	640.873		
Ex. Ca	Between Age groups	1	1953611.8	1953611.852	75.847**
	Error	18	463632.59	25757.366	
	Total	19	2417244.4		
Ex. Mg	Between Age groups	1	24860.919	24860.919	.855
	Error	18	523343.17	29074.621	
	Total	19	548204.08		
Av. P	Between Age groups	1	74.817	74.817	7.329*
	Error	18	183.746	10.208	
	Total	19	258.562		
O.C	Between Age groups	1	4.487	4.487	21.694**
	Error	18	3.723	0.207	
	Total	19	8.211		
Total. N	Between Age groups	1	5948377.1	5948377.103	39.762**
	Error	18	2692798.3	149599.906	
	Total	19	8641175.4		
C/N	Between Age groups	1	56.126	56.126	14.053**
	Error	18	71.890	3.994	
	Total	19	128.016		

Appendix 35

ANOVA of chemical properties in 0-20cm depth for comparing between natural forest and eucalypts plantations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	1	3.616	3.616	81.729**
	Error	18	0.796	0.044	
	Total	19	4.413		
Ex. Base	Between Age groups	1	728.02	728.02	18.944**
	Error	18	691.73	38.43	
	Total	19	1419.75		
Ex. Na	Between Age groups	1	1521.07	1521.07	3.643
	Error	18	7515.37	417.52	
	Total	19	9036.45		
Ex. K	Between Age groups	1	64.27	64.27	.993
	Error	18	1165.26	64.74	
	Total	19	1229.54		
Ex. Ca	Between Age groups	1	5940906.7	5940906.67	82.235**
	Error	18	1300373.3	72242.96	
	Total	19	7241280.0		
Ex. Mg	Between Age groups	1	112320.27	112320.27	3.753
	Error	18	538728.53	29929.36	
	Total	19	651048.80		
Av. P	Between Age groups	1	71.24	71.24	7.112*
	Error	18	180.30	10.02	
	Total	19	251.54		
O.C	Between Age groups	1	12.90	12.90	50.033**
	Error	18	4.64	0.26	
	Total	19	17.54		
Total. N	Between Age groups	1	7826481.7	7826481.67	22.867**
	Error	18	6160672.5	342259.59	
	Total	19	13987154		
C/N	Between Age groups	1	9.83	9.83	3.234
	Error	18	54.71	3.04	
	Total	19	64.54		

Appendix 36

ANOVA of chemical properties in 20-40cm depth for comparing between natural forest and eucalypts plantations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	2	1.13	0.56	4.597
	Error	17	2.08	0.12	
	Total	19	3.21		
Ex. Base	Between Age groups	1	104.02	104.02	3.556
	Error	18	526.53	29.25	
	Total	19	630.55		
Ex. Na	Between Age groups	1	1586.20	1586.20	3.619
	Error	18	7888.46	438.25	
	Total	19	9474.67		
Ex. K	Between Age groups	1	288.64	288.64	4.836*
	Error	18	1074.27	59.68	
	Total	19	1362.91		
Ex. Ca	Between Age groups	1	1823526.7	1823526.67	61.599**
	Error	18	532853.33	29602.96	
	Total	19	2356380.0		
Ex. Mg	Between Age groups	1	13500.00	13500.00	.570
	Error	18	426643.20	23702.40	
	Total	19	440143.20		
Av. P	Between Age groups	1	69.94	69.94	6.367*
	Error	18	197.74	10.99	
	Total	19	267.68		
O.C	Between Age groups	1	5.57	5.57	13.976**
	Error	18	7.17	0.40	
	Total	19	12.74		
Total. N	Between Age groups	1	10550929	10550929.87	42.303**
	Error	18	4489403.3	249411.29	
	Total	19	15040333		
C/N	Between Age groups	1	117.45	117.45	14.511**
	Error	18	145.68	8.09	
	Total	19	263.13		

Appendix 37

ANOVA of chemical properties in 40-60cm depth for comparing between natural forest and eucalypts plantations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	2	1.18	0.59	8.381
	Error	17	1.20	0.07	
	Total	19	2.38		
Ex. Base	Between Age groups	2	75.30	37.65	2.256
	Error	17	283.70	16.69	
	Total	19	359.00		
Ex. Na	Between Age groups	2	4076.90	2038.45	19.912**
	Error	17	1740.38	102.38	
	Total	19	5817.28		
Ex. K	Between Age groups	2	110.04	55.02	1.334
	Error	17	701.40	41.26	
	Total	19	811.44		
Ex. Ca	Between Age groups	2	159420.00	79710.00	1.898
	Error	17	714080.00	42004.71	
	Total	19	873500.00		
Ex. Mg	Between Age groups	2	472923.20	236461.60	10.202
	Error	17	394036.80	23178.64	
	Total	19	866960.00		
Av. P	Between Age groups	2	197.18	98.59	7.023
	Error	17	238.66	14.04	
	Total	19	435.84		
O.C	Between Age groups	2	0.77	0.39	2.183
	Error	17	3.00	0.18	
	Total	19	3.77		
Total. N	Between Age groups	2	1991035.7	995517.83	3.916*
	Error	17	4321896.9	254229.23	
	Total	19	6312932.6		
C/N	Between Age groups	2	129.88	64.94	7.551*
	Error	17	146.19	8.60	
	Total	19	276.07		

Appendix 38

ANOVA of chemical properties in 0-60cm depth between natural forest and teak plantations of different age class in location I

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	2	0.04173	0.02086	.910
	Error	14	0.321	0.02293	
	Total	16	0.363		
Ex. Base	Between Age groups	2	1.673	.837	.129
	Error	14	91.111	6.508	
	Total	16	92.784		
Ex. Na	Between Age groups	2	0.02192	0.01096	.099
	Error	14	1.547	0.111	
	Total	16	1.569		
Ex. K	Between Age groups	2	9.396	4.698	2.810
	Error	14	23.405	1.672	
	Total	16	32.801		
Ex. Ca	Between Age groups	2	15775.836	7887.918	3.137
	Error	14	35200.635	2514.331	
	Total	16	50976.471		
Ex. Mg	Between Age groups	2	1165.080	582.540	.635
	Error	14	12853.390	918.099	
	Total	16	14018.471		
Av. P	Between Age groups	2	1.320	0.660	1.408
	Error	14	6.567	0.469	
	Total	16	7.887		
O.C	Between Age groups	2	3.064	1.532	28.166**
	Error	14	0.762	0.05440	
	Total	16	3.826		
Total. N	Between Age groups	2	122321.19	61160.598	.154
	Error	14	5546142.8	396153.061	
	Total	16	5668464.0		
C/N	Between Age groups	2	63.911	31.955	12.378**
	Error	14	36.142	2.582	
	Total	16	100.053		

Appendix 39

ANOVA of chemical properties in 0-20cm depth between natural forest and teak plantations of different age class in location I

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	2	0.131	0.065	2.245
	Error	14	0.408	0.029	
	Total	16	0.539		
Ex. Base	Between Age groups	2	1.089	0.545	.067
	Error	14	113.029	8.073	
	Total	16	114.118		
Ex. Na	Between Age groups	2	0.052	0.026	.141
	Error	14	2.557	0.183	
	Total	16	2.609		
Ex. K	Between Age groups	2	7.106	3.553	1.692
	Error	14	29.390	2.099	
	Total	16	36.495		
Ex. Ca	Between Age groups	2	42984.202	21492.101	4.500*
	Error	14	66862.857	4775.918	
	Total	16	109847.06		
Ex. Mg	Between Age groups	2	948.430	474.215	.283
	Error	14	23440.629	1674.331	
	Total	16	24389.059		
Av. P	Between Age groups	2	12.501	6.250	4.488*
	Error	14	19.496	1.393	
	Total	16	31.997		
O.C	Between Age groups	2	4.903	2.451	22.580**
	Error	14	1.520	0.109	
	Total	16	6.423		
Total. N	Between Age groups	2	44823.529	22411.765	.038
	Error	14	8249000.0	589214.286	
	Total	16	8293823.5		
C/N	Between Age groups	2	47.767	23.883	13.251**
	Error	14	25.233	1.802	
	Total	16	73.000		

Appendix 40

ANOVA of chemical properties in 20-40cm depth between natural forest and teak plantations of different age class in location I.

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	2	0.018	0.009	.363
	Error	14	0.340	0.024	
	Total	16	0.358		
Ex. Base	Between Age groups	2	10.407	5.203	.730
	Error	14	99.829	7.131	
	Total	16	110.235		
Ex. Na	Between Age groups	2	0.001	0.000	.003
	Error	14	2.334	0.167	
	Total	16	2.334		
Ex. K	Between Age groups	2	7.729	3.865	1.196
	Error	14	45.235	3.231	
	Total	16	52.964		
Ex. Ca	Between Age groups	2	2468.571	1234.286	.343
	Error	14	50331.429	3595.102	
	Total	16	52800.000		
Ex. Mg	Between Age groups	2	10368.403	5184.202	4.392*
	Error	14	16525.714	1180.408	
	Total	16	26894.118		
Av. P	Between Age groups	2	0.160	0.080	.279
	Error	14	4.025	0.287	
	Total	16	4.185		
O.C	Between Age groups	2	2.879	1.439	27.060**
	Error	14	0.745	0.053	
	Total	16	3.624		
Total. N	Between Age groups	2	1545680.7	772840.336	1.091
	Error	14	9913142.9	708081.633	
	Total	16	11458823.6		
C/N	Between Age groups	2	82.525	41.262	6.769**
	Error	14	85.345	6.096	
	Total	16	167.869		

Appendix 41

ANOVA of chemical properties in 40-60cm depth between natural forest and teak plantations of different age class in location I

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	2	0.048	0.024	.733
	Error	14	0.461	0.033	
	Total	16	0.509		
Ex. Base	Between Age groups	2	6.329	3.165	.398
	Error	14	111.200	7.943	
	Total	16	117.529		
Ex. Na	Between Age groups	2	0.099	0.049	.285
	Error	14	2.430	0.174	
	Total	16	2.529		
Ex. K	Between Age groups	2	19.570	9.785	3.363
	Error	14	40.732	2.909	
	Total	16	60.303		
Ex. Ca	Between Age groups	2	15247.059	7623.529	1.224
	Error	14	87200.000	6228.571	
	Total	16	102447.06		
Ex. Mg	Between Age groups	2	731.536	365.768	.206
	Error	14	24848.229	1774.873	
	Total	16	25579.765		
Av. P	Between Age groups	2	0.892	0.446	1.453
	Error	14	4.298	0.307	
	Total	16	5.191		
O.C	Between Age groups	2	1.892	0.946	17.807**
	Error	14	0.744	0.053	
	Total	16	2.636		
Total. N	Between Age groups	2	170890.76	85445.378	.162
	Error	14	7390285.7	527877.551	
	Total	16	7561176.5		
C/N	Between Age groups	2	71.898	35.949	9.731**
	Error	14	51.721	3.694	
	Total	16	123.619		

Appendix 42

ANOVA of chemical properties in 0-60cm depth between natural forest and teak plantations of different age class in location II

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	2	0.562	0.281	12.126**
	Error	16	0.371	0.02316	
	Total	18	0.932		
Ex. Base	Between Age groups	2	18.241	9.121	3.770*
	Error	16	38.706	2.419	
	Total	18	56.947		
Ex. Na	Between Age groups	2	51.968	25.984	4.099*
	Error	16	101.437	6.340	
	Total	18	153.406		
Ex. K	Between Age groups	2	147.124	73.562	17.236**
	Error	16	68.288	4.268	
	Total	18	215.411		
Ex. Ca	Between Age groups	2	7713.684	3856.842	1.409
	Error	16	43782.222	2736.389	
	Total	18	51495.906		
Ex. Mg	Between Age groups	2	5373.748	2686.874	4.847*
	Error	16	8869.600	554.350	
	Total	18	14243.348		
Av. P	Between Age groups	2	1.299	0.649	3.739*
	Error	16	2.779	0.174	
	Total	18	4.077		
O.C	Between Age groups	2	0.220	0.110	9.691**
	Error	16	0.181	1.133E-02	
	Total	18	0.401		
Total. N	Between Age groups	2	364511.79	182255.897	1.807
	Error	16	1613375.0	100835.943	
	Total	18	1977886.8		
C/N	Between Age groups	2	11.751	5.876	6.838**
	Error	16	13.747	0.859	
	Total	18	25.499		

Appendix 43

ANOVA of chemical properties in 0-20cm depth between natural forest and teak plantations of different age class in location II

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	2	0.728	0.364	14.975**
	Error	16	0.389	0.024	
	Total	18	1.117		
pH	Between Age groups	2	17.469	8.735	1.711
	Error	16	81.689	5.106	
	Total	18	99.158		
Ex. Base	Between Age groups	2	18.231	9.116	1.136
	Error	16	128.378	8.024	
	Total	18	146.609		
Ex. Na	Between Age groups	2	39.840	19.920	3.401
	Error	16	93.718	5.857	
	Total	18	133.558		
Ex. K	Between Age groups	2	4059.883	2029.942	.898
	Error	16	36182.222	2261.389	
	Total	18	40242.105		
Ex. Ca	Between Age groups	2	1549.921	774.961	.822
	Error	16	15080.000	942.500	
	Total	18	16629.921		
Ex. Mg	Between Age groups	2	0.324	0.162	.473
	Error	16	5.482	0.343	
	Total	18	5.806		
Av. P	Between Age groups	2	0.919	0.459	31.274**
	Error	16	0.235	0.015	
	Total	18	1.154		
O.C	Between Age groups	2	32571.153	16285.576	.061
	Error	16	4256315.2	266019.702	
	Total	18	4288886.4		
Total. N	Between Age groups	2	7.397	3.698	1.027
	Error	16	57.644	3.603	
	Total	18	65.040		

Appendix 44

ANOVA of chemical properties in 20-40cm depth between natural forest and teak plantations of different age class in location II

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	2	0.571	0.285	14.470**
	Error	16	0.316	0.020	
	Total	18	0.886		
Ex. Base	Between Age groups	2	5.181	2.591	.372
	Error	16	111.556	6.972	
	Total	18	116.737		
Ex. Na	Between Age groups	2	58.766	29.383	3.992*
	Error	16	117.775	7.361	
	Total	18	176.541		
Ex. K	Between Age groups	2	244.123	122.062	16.114**
	Error	16	121.196	7.575	
	Total	18	365.319		
Ex. Ca	Between Age groups	2	25870.409	12935.205	2.875
	Error	16	71982.222	4498.889	
	Total	18	97852.632		
Ex. Mg	Between Age groups	2	3852.416	1926.208	1.007
	Error	16	30597.689	1912.356	
	Total	18	34450.105		
Av. P	Between Age groups	2	1.156	0.578	5.519*
	Error	16	1.676	0.105	
	Total	18	2.832		
O.C	Between Age groups	2	0.123	0.061	1.762
	Error	16	0.557	0.035	
	Total	18	0.680		
Total. N	Between Age groups	2	614963.4	307481.699	2.584
	Error	16	1904022.2	119001.389	
	Total	18	2518985.6		
C/N	Between Age groups	2	8.000	4.000	6.278*
	Error	16	10.194	0.637	
	Total	18	18.193		

Appendix 45

ANOVA of chemical properties in 40-60cm depth between natural forest and teak plantations of different age class in location II

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	2	0.511	0.256	3.601
	Error	16	1.136	0.071	
	Total	18	1.647		
Ex. Base	Between Age groups	2	62.737	31.368	3.983*
	Error	16	126.000	7.875	
	Total	18	188.737		
Ex. Na	Between Age groups	2	94.654	47.327	4.056*
	Error	16	186.676	11.667	
	Total	18	281.329		
Ex. K	Between Age groups	2	213.637	106.818	17.678**
	Error	16	96.677	6.042	
	Total	18	310.314		
Ex. Ca	Between Age groups	2	25094.737	12547.368	1.887
	Error	16	106400.00	6650.000	
	Total	18	131494.73		
Ex. Mg	Between Age groups	2	15339.181	7669.591	10.203*
	Error	16	12027.556	751.722	
	Total	18	27366.737		
Av. P	Between Age groups	2	4.415	2.208	6.187*
	Error	16	5.709	0.357	
	Total	18	10.124		
O.C	Between Age groups	2	0.018	0.009	.253
	Error	16	0.584	0.037	
	Total	18	0.603		
Total. N	Between Age groups	2	897144.536	448572.268	1.715
	Error	16	4184576.3	261536.018	
	Total	18	5081720.8		
C/N	Between Age groups	2	22.892	11.446	4.165*
	Error	16	43.974	2.748	
	Total	18	66.867		

Appendix 46

ANOVA of chemical properties in 0-60cm depth between natural forest and eucalypt plantations of different rotations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	3	2.382	0.794	27.739**
	Error	16	.458	2.862E-02	
	Total	19	2.839		
Ex. Base	Between Age groups	3	205.889	68.630	6.541**
	Error	16	167.867	10.492	
	Total	19	373.756		
Ex. Na	Between Age groups	3	5002.125	1667.375	16.829**
	Error	16	1585.228	99.077	
	Total	19	6587.353		
Ex. K	Between Age groups	3	178.323	59.441	2.056
	Error	16	462.550	28.909	
	Total	19	640.873		
Ex. Ca	Between Age groups	3	1976675.55	658891.852	23.929**
	Error	16	440568.889	27535.556	
	Total	19	2417244.44		
Ex. Mg	Between Age groups	3	501679.644	167226.548	57.510**
	Error	16	46524.444	2907.778	
	Total	19	548204.089		
Av. P	Between Age groups	3	125.026	41.675	4.993*
	Error	16	133.536	8.346	
	Total	19	258.562		
O.C	Between Age groups	3	5.437	1.812	10.455**
	Error	16	2.774	0.173	
	Total	19	8.211		
Total. N	Between Age groups	3	6770280.60	2256760.202	19.300**
	Error	16	1870894.80	116930.925	
	Total	19	8641175.41		
C/N	Between Age groups	3	88.137	29.379	11.787**
	Error	16	39.879	2.492	
	Total	19	128.016		

Appendix 47

ANOVA of chemical properties in 0-20cm depth between natural forest and eucalypt plantations of different rotations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	3	3.769	1.256	31.229**
	Error	16	0.644	0.040	
	Total	19	4.413		
Ex. Base	Between Age groups	3	921.750	307.250	9.871**
	Error	16	498.000	31.125	
	Total	19	1419.750		
Ex. Na	Between Age groups	3	5957.006	1985.669	10.317**
	Error	16	3079.440	192.465	
	Total	19	9036.445		
Ex. K	Between Age groups	3	322.182	107.394	1.894
	Error	16	907.356	56.710	
	Total	19	1229.538		
Ex. Ca	Between Age groups	3	6091360.0	2030453.333	28.252**
	Error	16	1149920.0	71870.000	
	Total	19	7241280.0		
Ex. Mg	Between Age groups	3	591784.80	197261.600	53.256**
	Error	16	59264.000	3704.000	
	Total	19	651048.80		
Av. P	Between Age groups	3	89.470	29.823	2.944
	Error	16	162.072	10.130	
	Total	19	251.542		
O.C	Between Age groups	3	14.347	4.782	24.007**
	Error	16	3.187	0.199	
	Total	19	17.535		
Total. N	Between Age groups	3	10783378.2	3594459.400	17.951**
	Error	16	3203776.00	200236.000	
	Total	19	13987154.2		
C/N	Between Age groups	3	34.433	11.478	6.100**
	Error	16	30.105	1.882	
	Total	19	64.538		

Appendix 47

ANOVA of chemical properties in 0-20cm depth between natural forest and eucalypt plantations of different rotations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	3	3.769	1.256	31.229**
	Error	16	0.644	0.040	
	Total	19	4.413		
Ex. Base	Between Age groups	3	921.750	307.250	9.871**
	Error	16	498.000	31.125	
	Total	19	1419.750		
Ex. Na	Between Age groups	3	5957.006	1985.669	10.317**
	Error	16	3079.440	192.465	
	Total	19	9036.445		
Ex. K	Between Age groups	3	322.182	107.394	1.894
	Error	16	907.356	56.710	
	Total	19	1229.538		
Ex. Ca	Between Age groups	3	6091360.0	2030453.333	28.252**
	Error	16	1149920.0	71870.000	
	Total	19	7241280.0		
Ex. Mg	Between Age groups	3	591784.80	197261.600	53.256**
	Error	16	59264.000	3704.000	
	Total	19	651048.80		
Av. P	Between Age groups	3	89.470	29.823	2.944
	Error	16	162.072	10.130	
	Total	19	251.542		
O.C	Between Age groups	3	14.347	4.782	24.007**
	Error	16	3.187	0.199	
	Total	19	17.535		
Total. N	Between Age groups	3	10783378.2	3594459.400	17.951**
	Error	16	3203776.00	200236.000	
	Total	19	13987154.2		
C/N	Between Age groups	3	34.433	11.478	6.100**
	Error	16	30.105	1.882	
	Total	19	64.538		

Appendix 48

ANOVA of chemical properties in 20-40cm depth between natural forest and eucalypt plantations of different rotations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	3	2.452	0.817	17.247**
	Error	16	0.758	0.047	
	Total	19	3.210		
Ex. Base	Between Age groups	3	286.550	95.517	4.443*
	Error	16	344.000	21.500	
	Total	19	630.550		
Ex. Na	Between Age groups	3	5112.109	1704.036	6.250**
	Error	16	4362.556	272.660	
	Total	19	9474.665		
Ex. K	Between Age groups	3	337.228	112.409	1.754
	Error	16	1025.680	64.105	
	Total	19	1362.908		
Ex. Ca	Between Age groups	3	1848540.0	616180.000	19.413**
	Error	16	507840.00	31740.000	
	Total	19	2356380.0		
Ex. Mg	Between Age groups	3	342914.40	114304.800	18.810**
	Error	16	97228.800	6076.800	
	Total	19	440143.20		
Av. P	Between Age groups	3	119.534	39.845	4.303*
	Error	16	148.146	9.259	
	Total	19	267.680		
O.C	Between Age groups	3	6.493	2.164	5.542**
	Error	16	6.249	0.391	
	Total	19	12.742		
Total. N	Between Age groups	3	11033038.6	3677679.538	14.684**
	Error	16	4007294.53	250455.908	
	Total	19	15040333.1		
C/N	Between Age groups	3	142.710	47.570	6.320**
	Error	16	120.422	7.526	
	Total	19	263.132		

Appendix 49

ANOVA of chemical properties in 40-60cm depth between natural forest and eucalypt plantations of different rotations

Variables	Source	df	Sum of Squares	Mean Square	F
pH	Between Age groups	3	1.446	0.482	8.223**
	Error	16	0.938	0.059	
	Total	19	2.384		
Ex. Base	Between Age groups	3	97.800	32.600	1.997
	Error	16	261.200	16.325	
	Total	19	359.000		
Ex. Na	Between Age groups	3	4185.137	1395.046	13.676**
	Error	16	1632.140	102.009	
	Total	19	5817.277		
Ex. K	Between Age groups	3	144.266	48.089	1.153
	Error	16	667.172	41.698	
	Total	19	811.438		
Ex. Ca	Between Age groups	3	205660.000	68553.333	1.642
	Error	16	667840.000	41740.000	
	Total	19	873500.000		
Ex. Mg	Between Age groups	3	658972.800	219657.600	16.898**
	Error	16	207987.200	12999.200	
	Total	19	866960.000		
Av. P	Between Age groups	3	207.380	69.127	4.841*
	Error	16	228.463	14.279	
	Total	19	435.843		
O.C	Between Age groups	3	0.776	0.259	1.384
	Error	16	2.993	0.187	
	Total	19	3.769		
Total. N	Between Age groups	3	2420768.55	806922.850	3.317*
	Error	16	3892164.00	243260.250	
	Total	19	6312932.55		
C/N	Between Age groups	3	155.799	51.933	6.909**
	Error	16	120.271	7.517	
	Total	19	276.071		

Appendix 50

Mean of chemical properties in Location 1

0-20cm

Age class	pH	Ex. Bases	Ex. Na ppm	Ex. K ppm	Ex. Ca ppm	Ex. Mg ppm	Av. P ppm	OC per cent	Total. N ppm.	C/N
NF	5.4	6.80	4.2	5.0	254[a]	117	1.2[a]	2.6[a]	2890	9.0[a]
21-30 TP	5.2	6.20	4.3	3.4	280[a]	103	0.8[a]	1.5[b]	2760	6.0[b]
31-40 TP	5.4	6.29	4.2	3.9	367[b]	99	2.7[b]	1.4[b]	2800	5.0[b]

20-40cm

Age class	pH	Ex. Bases	Ex. Na ppm	Ex. K ppm	Ex. Ca ppm	Ex. Mg ppm	Av. P ppm	OC per cent	Total. N ppm.	C/N
NF	5.3	4.40	4.3	6.6	208	44[b]	0.6	1.8[a]	2320	9.3[a]
21-30 TP	5.2	6.40	4.3	5.2	212	106[a]	0.5	1.1[b]	1580	7.4[a]
31-40 TP	5.3	5.71	4.3	6.7	234	89[a]	0.7	0.8[c]	2157	4.1[b]

40-60cm

Age class	pH	Ex. Bases	Ex. Na ppm	Ex. K ppm	Ex. Ca ppm	Ex. Mg ppm	Av. P ppm	OC per cent	Total. N ppm.	C/N
NF	5.2	4.60	4.4	6.8[a]	188	62	0.7	1.5[a]	1620	9.2[a]
21-30 TP	5.3	5.00	4.3	4.5[b]	224	77	0.3	1.0[b]	1880	5.6[b]
31-40 TP	5.4	6.00	4.3	6.8[a]	260	76	0.2	0.7[c]	1771	4.3[c]

0-60cm

Age class	pH	Ex. Bases	Ex. Na ppm	Ex. K ppm	Ex. Ca ppm	Ex. Mg ppm	Av. P ppm	OC per cent	Total. N ppm.	C/N
NF	5.3	5.3	4	6	217	74	0.8	2.0[a]	2277	9.2[a]
21-30 TP	5.2	5.9	4	4	239	96	0.5	1.2[b]	2073	6.4[b]
31-40 TP	5.4	6.0	4	6	287	88	1.2	0.9[b]	2243	4.5[b]

Mean of chemical properties in Location 2

0-20cm

Age class	pH	Ex. Bases	Ex. Na ppm	Ex. K ppm	Ex. Ca ppm	Ex. Mg ppm	Av. P ppm	OC per cent	Total. N ppm.	C/N
NF	4.6[a]	6.80	5.8	9.6[a]	352	151	1.9	2.8[a]	3332	8.3
41-50 TP	4.9[b]	8.00	6.5	7.6[a]	392	127	1.6	2.3[b]	3421	7.7
≥50 TP	5.1[c]	9.11	8.0	6.1[b]	375	134	1.9	2.2[b]	3429	6.9

20-40cm

Age class	pH	Ex. Bases	Ex. Na ppm	Ex. K ppm	Ex. Ca ppm	Ex. Mg ppm	Av. P ppm	OC per cent	Total. N ppm.	C/N
NF	4.7[b]	8.80	4.5[b]	12.1[a]	308[a]	134	1.3[a]	1.7	2241	7.7[a]
41-50 TP	5.0[a]	7.60	6.4[ab]	6.7[b]	212[b]	94	0.6[b]	1.5	2207	6.9[ab]
≥50 TP	5.1[a]	8.78	8.7[a]	3.4[c]	284[ab]	113	1.0[ab]	1.6	2584	6.1[b]

40-60cm

Age class	pH	Ex. Bases	Ex. Na ppm	Ex. K ppm	Ex. Ca ppm	Ex. Mg ppm	Av. P ppm	OC per cent	Total. N ppm.	C/N
NF	4.7^{a}	8.40^{b}	4.2^{b}	11.4^{a}	296	138^{a}	1.7^{a}	1.3	1424	8.9^{a}
41-50 TP	5.1^{b}	7.20^{b}	6.2^{b}	5.1^{b}	232	62^{b}	0.6^{b}	1.2	1706	7.2^{ba}
≥50 TP	5.0^{b}	11.33^{a}	9.4^{a}	3.3^{b}	320	114^{a}	0.7^{b}	1.2	1950	6.2^{b}

0-60cm

Age class	pH	Ex. Bases	Ex. Na ppm	Ex. K ppm	Ex. Ca ppm	Ex. Mg ppm	Av. P ppm	OC per cent	Total. N ppm.	C/N
NF	4.7^{a}	8.0^{ab}	5^{a}	11^{a}	319	141^{a}	1.7^{a}	1.91^{a}	2333	8.3^{a}
41-50 TP	5.0^{b}	7.6^{b}	6^{a}	6^{b}	279	95^{b}	1.0^{b}	1.6^{b}	2445	7.2^{ab}
≥50 TP	5.1^{b}	9.7^{a}	9^{b}	4^{b}	327	120^{ab}	1.2^{ab}	1.7^{b}	2654	6.4^{b}

Mean of chemical properties in Location 3

0-20cm

Age class	pH	Ex. Bases	Ex. Na ppm	Ex. K ppm	Ex. Ca ppm	Ex. Mg ppm	Av. P ppm	OC per cent	Total. N ppm.	C/N
N.F	6.5^{a}	37.20^{a}	21.5^{b}	25.0	1848^{a}	530^{a}	3.5^{a}	4.3^{a}	3275^{a}	11.3^{b}
E II	5.7^{b}	27.60^{b}	18.3^{b}	24.0	704^{b}	587^{a}	6.5^{ab}	2.6^{b}	2335^{b}	11.1^{b}
E III C	5.6^{b}	23.40^{bc}	47.1^{a}	15.0	604^{b}	334^{b}	7.8^{b}	2.0^{c}	1254^{d}	13.7^{a}
E III R	5.4^{b}	18.80^{c}	59.4^{a}	23.6	460^{b}	151^{c}	9.2^{b}	2.7^{b}	1902^{c}	14.0^{a}

20-40cm

Age class	pH	Ex. Bases	Ex. Na ppm	Ex. K ppm	Ex. Ca ppm	Ex. Mg ppm	Av. P ppm	OC per cent	Total. N ppm.	C/N
N.F	6.3^{a}	27.60^{a}	21.2^{b}	24.9^{a}	1124^{a}	364^{b}	1.7^{b}	2.9^{a}	2848^{a}	8.5^{b}
E II	5.6^{b}	24.80^{a}	21.6^{b}	17.9^{ab}	404^{b}	492^{a}	3.5^{ab}	1.8^{b}	1367^{b}	12.5^{a}
E III C	5.5^{b}	17.40^{b}	44.7^{a}	13.7^{b}	392^{b}	293^{b}	7.1^{a}	1.3^{b}	934^{b}	14.3^{a}
E III R	5.5^{b}	24.80^{a}	58.8^{a}	16.9^{ab}	484^{b}	130^{c}	7.6^{a}	1.9^{b}	1211^{b}	15.7^{a}

40-60cm

Age class	pH	Ex. Bases	Ex. Na ppm	Ex. K ppm	Ex. Ca ppm	Ex. Mg ppm	Av. P ppm	OC per cent	Total. N ppm.	C/N
N.F	6.1^{a}	20.80^{bc}	23.1^{b}	12.5	672	382^{b}	1.9^{b}	1.4	1930^{a}	6.2^{b}
E II	5.8^{ab}	23.80^{b}	29.6^{b}	16.2	536	655^{a}	3.9^{b}	1.4	1516^{ab}	9.4^{b}
E III C	5.4^{c}	23.20^{bc}	50.6^{a}	10.5	416	302^{c}	5.3^{b}	0.9	1345^{ab}	8.5^{b}
E III R	5.5^{bc}	18.20^{c}	58.2^{a}	17.1	436	156^{c}	10.6^{a}	1.4	962^{b}	13.9^{a}

0-60cm

Age class	pH	Ex. Bases	Ex. Na ppm	Ex. K ppm	Ex. Ca ppm	Ex. Mg ppm	Av. P ppm	OC per cent	Total. N ppm.	C/N
N.F	6.3^{a}	29^{a}	22^{a}	21	1215^{a}	426^{a}	2^{a}	2.85^{a}	2685^{a}	8.7^{a}
E II	5.7^{b}	25^{ca}	23^{a}	19	548^{b}	578^{c}	5^{ac}	1.90^{bc}	1739^{b}	11.0^{b}
E III C	5.5^{b}	21^{bc}	47^{b}	13	471^{b}	310^{b}	7^{bc}	1.41^{c}	1178^{c}	12.1^{b}
E III R	5.4^{b}	21^{b}	59^{b}	19	460^{b}	146^{b}	9^{b}	1.97^{b}	1358^{bc}	14.5^{c}

Figures with different superscript differ significantly from each other.

NF –Natural forest, TP – Teak plantation,
EII – Eucalypt II[nd] rotation, EIII C – Eucalypt III[rd] rotation coppiced, EIII R - Eucalypt III[rd] rotation replanted

Appendix 51

ANOVA of micronutrients in 0-60cm depth for comparing between natural forest and younger teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	1	19.438	19.438	6.822*
	Within Groups	15	42.737	2.849	
	Total	16	62.174		
Ex. Cu	Between Groups	1	0.06761	0.06761	65.908**
	Within Groups	15	0.01539	0.001026	
	Total	16	0.08299		
Ex. Zn	Between Groups	1	0.0001821	0.0001821	.161
	Within Groups	15	0.01701	0.001134	
	Total	16	0.01719		
Ex. Mn	Between Groups	1	6.395	6.395	1.504
	Within Groups	15	63.804	4.254	
	Total	16	70.200		

Appendix 52

ANOVA of micronutrients in 0-20cm depth for comparing between natural forest and younger teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	1	27.50	27.50	6.544*
	Within Groups	15	63.03	4.20	
	Total	16	90.52		
Ex. Cu	Between Groups	1	0.06	0.06	69.065**
	Within Groups	15	0.01	0.00	
	Total	16	0.07		
Ex. Zn	Between Groups	1	0.00	0.00	.381
	Within Groups	15	0.05	0.00	
	Total	16	0.05		
Ex. Mn	Between Groups	1	21.82	21.82	2.275
	Within Groups	15	143.84	9.59	
	Total	16	165.66		

Appendix 53

ANOVA of micronutrients in 20-40cm depth for comparing between natural forest and younger teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	1	18.01	18.01	6.551*
	Within Groups	15	41.23	2.75	
	Total	16	59.24		
Ex. Cu	Between Groups	1	0.08	0.08	38.531**
	Within Groups	15	0.03	0.00	
	Total	16	0.11		
Ex. Zn	Between Groups	1	0.00	0.00	.025
	Within Groups	15	0.01	0.00	
	Total	16	0.01		
Ex. Mn	Between Groups	1	0.92	0.92	.671
	Within Groups	15	20.65	1.38	
	Total	16	21.57		

Appendix 54

ANOVA of micronutrients in 40-60cm depth for comparing between natural forest and younger teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	1	13.98	13.98	4.550*
	Within Groups	15	46.10	3.07	
	Total	16	60.08		
Ex. Cu	Between Groups	1	0.07	0.07	24.318**
	Within Groups	15	0.04	0.00	
	Total	16	0.11		
Ex. Zn	Between Groups	1	0.00	0.00	.058
	Within Groups	15	0.02	0.00	
	Total	16	0.02		
Ex. Mn	Between Groups	1	3.82	3.82	.652
	Within Groups	15	87.92	5.86	
	Total	16	91.74		

Appendix 55

ANOVA of micronutrients in 0-60cm depth for comparing between natural forest and older teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	1	2.911	2.911	3.438
	Within Groups	17	14.397	.847	
	Total	18	17.308		
Ex. Cu	Between Groups	1	0.003765	0.03765	49.769**
	Within Groups	17	0.01286	0.0007564	
	Total	18	0.05050		
Ex. Zn	Between Groups	1	0.00002719	0.00002719	.047
	Within Groups	17	0.009760	0.0005741	
	Total	18	0.009787		
Ex. Mn	Between Groups	1	0.001925	0.001925	.003
	Within Groups	17	11.480	.675	
	Total	18	11.482		

Appendix 56

ANOVA of micronutrients in 0-20cm depth for comparing between natural forest and older teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	1	19.38	19.38	23.082**
	Within Groups	17	14.27	0.84	
	Total	18	33.65		
Ex. Cu	Between Groups	1	0.03	0.03	18.407**
	Within Groups	17	0.02	0.00	
	Total	18	0.05		
Ex. Zn	Between Groups	1	0.00	0.00	4.654*
	Within Groups	17	0.02	0.00	
	Total	18	0.02		
Ex. Mn	Between Groups	1	3.01	3.01	2.643
	Within Groups	17	19.33	1.14	
	Total	18	22.34		

Appendix 57

ANOVA of micronutrients in 20-40cm depth for comparing between natural forest and older teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	1	0.09	0.09	.064
	Within Groups	17	23.41	1.38	
	Total	18	23.49		
Ex. Cu	Between Groups	1	0.05	0.05	53.592**
	Within Groups	17	0.02	0.00	
	Total	18	0.07		
Ex. Zn	Between Groups	1	0.00	0.00	.744
	Within Groups	17	0.04	0.00	
	Total	18	0.04		
Ex. Mn	Between Groups	1	0.10	0.10	.105
	Within Groups	17	16.78	0.99	
	Total	18	16.88		

Appendix 58

ANOVA of micronutrients in 40-60cm depth for comparing between natural forest and older teak plantations

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	1	0.18	0.18	.214
	Within Groups	17	14.06	0.83	
	Total	18	14.23		
Ex. Cu	Between Groups	1	0.04	0.04	44.380**
	Within Groups	17	0.01	0.00	
	Total	18	0.05		
Ex. Zn	Between Groups	1	0.00	0.00	.262
	Within Groups	17	0.01	0.00	
	Total	18	0.01		
Ex. Mn	Between Groups	1	1.64	1.64	2.084
	Within Groups	17	13.38	0.79	
	Total	18	15.02		

Appendix 59

ANOVA of micronutrients in 0-60cm depth for comparing between natural forest and eucalypts plantations

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	1	1.619	1.619	5.155*
	Within Groups	18	5.654	.314	
	Total	19	7.273		
Ex. Cu	Between Groups	1	0.04254	0.04254	4.553*
	Within Groups	18	0.168	0.009343	
	Total	19	0.211		
Ex. Zn	Between Groups	1	0.0008042	0.0008042	.123
	Within Groups	18	0.117	6.519E-03	
	Total	19	0.118		
Ex. Mn	Between Groups	1	8.525	8.525	3.214
	Within Groups	18	47.747	2.653	
	Total	19	56.272		

Appendix 60

ANOVA of micronutrients in 0-20cm depth for comparing between natural forest and eucalypts plantations

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	1	1.07	1.07	10.203**
	Within Groups	18	1.89	0.11	
	Total	19	2.96		
Ex. Cu	Between Groups	1	0.01	0.01	1.659
	Within Groups	18	0.12	0.01	
	Total	19	0.13		
Ex. Zn	Between Groups	1	0.00	0.00	.138
	Within Groups	18	0.21	0.01	
	Total	19	0.21		
Ex. Mn	Between Groups	1	46.71	46.71	16.980**
	Within Groups	18	49.52	2.75	
	Total	19	96.23		

Appendix 61

ANOVA of micronutrients in 20-40cm depth for comparing between natural forest and eucalypts plantations

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	1	1.99	1.99	3.850
	Within Groups	18	9.31	0.52	
	Total	19	11.30		
Ex. Cu	Between Groups	1	0.01	0.01	.202
	Within Groups	18	0.47	0.03	
	Total	19	0.48		
Ex. Zn	Between Groups	1	0.00	0.00	.014
	Within Groups	18	0.09	0.01	
	Total	19	0.09		
Ex. Mn	Between Groups	1	1.64	1.64	.466
	Within Groups	18	63.35	3.52	
	Total	19	64.99		

Appendix 62

ANOVA of micronutrients in 40-60cm depth for comparing between natural forest and eucalypts plantations

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	1	1.88	1.88	2.938
	Within Groups	18	11.52	0.64	
	Total	19	13.40		
Ex. Cu	Between Groups	1	0.20	0.20	19.662**
	Within Groups	18	0.18	0.01	
	Total	19	0.37		
Ex. Zn	Between Groups	1	0.00	0.00	.165
	Within Groups	18	0.31	0.02	
	Total	19	0.32		
Ex. Mn	Between Groups	1	0.42	0.42	.095
	Within Groups	18	78.69	4.37	
	Total	19	79.11		

Appendix 63

ANOVA of micronutrients in 0-60cm depth between natural forest and teak plantations of different age class in location I.

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	2	48.219	24.110	24.187**
	Within Groups	14	13.955	.997	
	Total	16	62.174		
Ex. Cu	Between Groups	2	0.07027	0.03514	38.664**
	Within Groups	14	0.01272	0.0009087	
	Total	16	0.08299		
Ex. Zn	Between Groups	2	0.002427	0.00121	1.151
	Within Groups	14	0.01476	0.001055	
	Total	16	0.01719		
Ex. Mn	Between Groups	2	17.828	8.914	2.383
	Within Groups	14	52.372	3.741	
	Total	16	70.200		

Appendix 64

ANOVA of micronutrients in 0-20cm depth between natural forest and teak plantations of different age class in location 1.

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	2	6387.588	3193.794	16.779**
	Within Groups	14	2664.852	190.347	
	Total	16	9052.440		
Ex. Cu	Between Groups	2	5.707	2.854	38.941**
	Within Groups	14	1.026	0.07328	
	Total	16	6.733		
Ex. Zn	Between Groups	2	0.356	0.178	0.500
	Within Groups	14	4.979	0.356	
	Total	16	5.335		
Ex. Mn	Between Groups	2	4101.840	2050.920	2.304
	Within Groups	14	12464.325	890.309	
	Total	16	16566.165		

Appendix 65

ANOVA of micronutrients in 20-40cm depth between natural forest and teak plantations of different age class in location I.

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	2	3947.556	1973.778	13.985**
	Within Groups	14	1975.914	141.137	
	Total	16	5923.471		
Ex. Cu	Between Groups	2	9.329	4.664	31.290**
	Within Groups	14	2.087	.149	
	Total	16	11.416		
Ex. Zn	Between Groups	2	0.128	0.06404	0.746
	Within Groups	14	1.203	0.08590	
	Total	16	1.331		
Ex. Mn	Between Groups	2	315.635	157.818	1.200
	Within Groups	14	1841.762	131.554	
	Total	16	2157.398		

Appendix 66

ANOVA of micronutrients in 40-60cm depth between natural forest and teak plantations of different age class in location I.

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	2	1661.790	118.699	18.308**
	Within Groups	14	6008.035		
	Total	16	6.672	3.336	
Ex. Cu	Between Groups	2	4.106	0.293	11.374**
	Within Groups	14	10.778		
	Total	16	0.360	0.180	
Ex. Zn	Between Groups	2	1.663	0.119	1.517
	Within Groups	14	2.024		
	Total	16	2203.236	1101.618	
Ex. Mn	Between Groups	2	6970.854	497.918	2.212
	Within Groups	14	9174.091		
	Total	16	1661.790	118.699	

Appendix 67

ANOVA of micronutrients in 0-60cm depth between natural forest and teak plantations of different age class in location II.

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	2	4.399	2.199	2.726
	Within Groups	16	12.910	.807	
	Total	18	17.308		
Ex. Cu	Between Groups	2	0.03897	0.01949	27.032**
	Within Groups	16	0.01153	0.0007208	
	Total	18	0.05050		
Ex. Zn	Between Groups	2	0.001900	0.0009499	1.927
	Within Groups	16	0.007887	0.0004929	
	Total	18	0.009787		
Ex. Mn	Between Groups	2	4.903	2.451	5.962*
	Within Groups	16	6.579	.411	
	Total	18	11.482		

Appendix 68

ANOVA of micronutrients in 0-20cm depth between natural forest and teak plantations of different age class in location II.

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	2	2106.691	1053.346	13.398**
	Within Groups	16	1257.940	78.621	
	Total	18	3364.631		
Ex. Cu	Between Groups	2	2.756	1.378	9.000**
	Within Groups	16	2.449	0.153	
	Total	18	5.205		
Ex. Zn	Between Groups	2	0.550	0.275	2.614
	Within Groups	16	1.683	0.105	
	Total	18	2.233		
Ex. Mn	Between Groups	2	460.010	230.005	2.075
	Within Groups	16	1773.791	110.862	
	Total	18	2233.800		

Appendix 69

ANOVA of micronutrients in 20-40cm depth between natural forest and teak plantations of different age class in location II.

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	2	272.626	136.313	1.050
	Within Groups	16	2076.700	129.794	
	Total	18	2349.326		
Ex. Cu	Between Groups	2	5.045	2.523	26.075**
	Within Groups	16	1.548	0.09674	
	Total	18	6.593		
Ex. Zn	Between Groups	2	0.840	0.420	2.174
	Within Groups	16	3.090	0.193	
	Total	18	3.929		
Ex. Mn	Between Groups	2	777.917	388.958	6.837**
	Within Groups	16	910.300	56.894	
	Total	18	1688.217		

Appendix 70

ANOVA of micronutrients in 40-60cm depth between natural forest and teak plantations of different age class in location II.

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	2	71.549	35.775	0.423
	Within Groups	16	1351.780	84.486	
	Total	18	1423.329		
Ex. Cu	Between Groups	2	4.206	2.103	33.959**
	Within Groups	16	0.991	0.06193	
	Total	18	5.197		
Ex. Zn	Between Groups	2	0.06196	0.03098	0.467
	Within Groups	16	1.061	0.06630	
	Total	18	1.123		
Ex. Mn	Between Groups	2	844.415	422.208	10.270**
	Within Groups	16	657.769	41.111	
	Total	18	1502.184		

Appendix 71

ANOVA of micronutrients in the 0-60cm depth between natural forest and eucalypt plantations of different rotation.

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	3	6.675	2.225	59.481**
	Within Groups	16	.598	3.740E-02	
	Total	19	7.273		
Ex. Cu	Between Groups	3	.127	0.04219	8.022**
	Within Groups	16	0.08415	0.005259	
	Total	19	0.211		
Ex. Zn	Between Groups	3	0.04117	0.01372	2.852
	Within Groups	16	0.07698	0.004811	
	Total	19	0.118		
Ex. Mn	Between Groups	3	32.019	10.673	7.041**
	Within Groups	16	24.253	1.516	
	Total	19	56.272		

Appendix 72

ANOVA of micronutrients in the 0-20cm depth between natural forest and eucalypt plantations of different rotation.

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	3	223.282	74.427	16.302**
	Within Groups	16	73.048	4.566	
	Total	19	296.330		
Ex. Cu	Between Groups	3	3.980	1.327	2.425
	Within Groups	16	8.756	0.547	
	Total	19	12.736		
Ex. Zn	Between Groups	3	11.756	3.919	6.895**
	Within Groups	16	9.093	0.568	
	Total	19	20.849		
Ex. Mn	Between Groups	3	5666.806	1888.935	7.640**
	Within Groups	16	3955.912	247.245	
	Total	19	9622.718		

Appendix 73

ANOVA of micronutrients in the 20-40cm depth between natural forest and eucalypt plantations of different rotation

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	3	961.670	320.557	30.457**
	Within Groups	16	168.400	10.525	
	Total	19	1130.070		
Ex. Cu	Between Groups	3	23.796	7.932	5.264*
	Within Groups	16	24.111	1.507	
	Total	19	47.907		
Ex. Zn	Between Groups	3	3.430	1.143	3.245
	Within Groups	16	5.637	0.352	
	Total	19	9.068		
Ex. Mn	Between Groups	3	3558.612	1186.204	6.454**
	Within Groups	16	2940.540	183.784	
	Total	19	6499.152		

Appendix 74

ANOVA of micronutrients in the 40-60cm depth between natural forest and eucalypt plantations of different rotation

Variables	Source	df	Sum of Squares	Mean Square	F
Ex. Fe	Between Groups	3	1112.466	370.822	26.135**
	Within Groups	16	227.016	14.189	
	Total	19	1339.482		
Ex. Cu	Between Groups	3	24.890	8.297	10.569**
	Within Groups	16	12.560	0.785	
	Total	19	37.450		
Ex. Zn	Between Groups	3	3.191	1.064	0.596
	Within Groups	16	28.542	1.784	
	Total	19	31.733		
Ex. Mn	Between Groups	3	3241.630	1080.543	3.703*
	Within Groups	16	4669.000	291.813	
	Total	19	7910.630		

Appendix 75

Mean of micronutrient in Location 1

0-20cm

Age class	Ex. Fe	Ex. Cu	Ex. Zn	Ex. Mn
NF	14.5300^{b}	0.49100^{b}	1.44100	38.770
21-30 TP	21.8400^{b}	1.88600^{a}	1.08600	78.600
31-40 TP	57.1571^{a}	1.64071^{a}	1.36286	52.943

20-40cm

Age class	Ex. Fe	Ex. Cu	Ex. Zn	Ex. Mn
NF	16.4800^{b}	0.41000^{c}	0.88400	21.100
21-30 TP	23.2400^{b}	2.29600^{a}	0.78800	31.320
31-40 TP	50.3714^{a}	1.67857^{b}	0.99571	22.571

40-60cm

Age class	Ex. Fe	Ex. Cu	Ex. Zn	Ex. Mn
NF	18.8200^{b}	0.58400^{b}	0.96800	22.680
21-30 TP	20.1800^{b}	1.98400^{a}	0.71800	47.660
31-40 TP	51.9714^{a}	1.94000^{a}	1.06571	22.671

0-60cm

Age class	Ex. Fe	Ex. Cu	Ex. Zn	Ex. Mn
NF	16.6^{a}	0.47^{a}	1.10	27.52
21-30 TP	21.8^{a}	2.06^{b}	0.86	52.53
31-40 TP	53.2^{b}	1.75^{b}	1.14	32.73

Mean of micronutrients in Location 2

0-20cm

Age class	Ex. Fe	Ex. Cu	Ex. Zn	Ex. Mn
NF	42.9900^{a}	0.64600^{b}	1.74200^{a}	45.090
41-50 TP	24.7200^{b}	1.42310^{a}	1.47600^{ba}	31.530
≥50 TP	17.4667^{b}	1.54739^{a}	1.32833^{b}	38.572

20-40cm

Age class	Ex. Fe	Ex. Cu	Ex. Zn	Ex. Mn
NF	24.7800	0.58800^{b}	0.79000	24.440^{b}
41-50 TP	29.0600	1.68200^{a}	1.29600	16.180^{b}
≥50 TP	20.0000	1.79333^{a}	0.83778	31.633^{a}

40-60cm

Age class	Ex. Fe	Ex. Cu	Ex. Zn	Ex. Mn
NF	25.4200	0.5082^{a}	0.7220	17.020^{a}
41-50 TP	25.8600	01.27800^{b}	0.86600	14.340^{a}
≥50 TP	21.7667	01.65156^{c}	0.74778	28.889^{b}

0-60cm

Age class	Ex. Fe	Ex. Cu	Ex. Zn	Ex. Mn
NF	31.1	0.62^{a}	1.08	28.85^{ab}
41-50 TP	26.5	1.46^{b}	1.21	20.68^{b}
>50 TP	19.7	1.66^{b}	0.97	33.03^{a}

Mean of micronutrients in Location 3

0-20cm

Age class	Ex. Fe	Ex. Cu	Ex. Zn	Ex. Mn
N.F	7.6400^{b}	2.18800^{a}	2.17000^{b}	66.580^{a}
E II	9.4000^{b}	2.11800^{a}	3.60000^{a}	42.620^{b}
E III C	16.1800^{a}	1.77800^{ac}	1.95000^{b}	27.420^{b}
E III R	13.3800^{a}	1.06200^{bc}	1.57600^{b}	23.820^{b}

20-40cm

Age class	Ex. Fe	Ex. Cu	Ex. Zn	Ex. Mn
N.F	8.4400^{b}	2.55400^{ab}	1.18000^{ab}	36.340^{ab}
E II	10.3000^{b}	3.88000^{a}	1.81000^{a}	50.920^{a}
E III C	25.8000^{a}	1.71600^{b}	0.84800^{b}	20.740^{bc}
E III R	11.0800^{b}	0.93600^{b}	0.75200^{b}	17.520^{c}

40-60cm

Age class	Ex. Fe	Ex. Cu	Ex. Zn	Ex. Mn
N.F	11.1600^{b}	3.89400^{a}	1.20000	33.300^{ab}
E II	11.5600^{b}	2.36800^{b}	1.76200	49.400^{a}
E III C	29.2600^{a}	1.55400^{bc}	0.85600	26.340^{b}
E III R	13.9000^{b}	0.91000^{c}	1.81400	14.180^{b}

0-60cm

Age class	Ex. Fe	Ex. Cu	Ex. Zn	Ex. Mn
N.F	9.08^{a}	2.88^{a}	1.52	45.41^{a}
E II	10.42^{ca}	2.79^{a}	2.39	47.65^{a}
E III C	23.75^{ba}	1.68^{b}	1.22	24.83^{b}
E III R	12.79^{d}	0.97^{b}	1.38	18.51^{b}

Figures with different superscript differ significantly from each other

NF –Natural forest, TP – Teak plantation,
EII – Eucalypt IInd rotation, EIII C – Eucalypt IIIrd rotation coppiced, EIII R - Eucalypt IIIrd rotation replanted

Appendix 76

Correlation among soil variables

		G	S	SI	CLY	BD	PD	PS	WHC	PH	E.B	Na	K	Ca	Mg	P	OC	T.N.	C/N	Fe	Cu	Zn	Mn
G	Pearson Correlation	1.000																					
	Sig. (2-tailed)																						
	N	168																					
S	Pearson Correlation	104	1.000																				
	Sig. (2-tailed)	.178																					
	N	168	168																				
SI	Pearson Correlation	.039	-.485	1.000																			
	Sig. (2-tailed)	.617	.000	.																			
	N	168	168	168																			
CLY	Pearson Correlation	-.148	-.825	-.094	1.000																		
	Sig. (2-tailed)	.056	.000	.224																			
	N	168	168	168	168																		
BD	Pearson Correlation	.388	.240	-.302	-.080	1.000																	
	Sig. (2-tailed)	.000	.002	.000	.302																		
	N	168	168	168	168	168																	
PD	Pearson Correlation	.151	-.036	-.081	.095	.465	1.000																
	Sig. (2-tailed)	.051	.641	.295	.222	.000																	
	N	168	168	168	168	168	168																
PS	Pearson Correlation	-.345	-.269	.297	.118	-.839	.030	1.000															
	Sig. (2-tailed)	.000	.000	.000	.128	.000	.699																
	N	168	168	168	168	168	168	168															
WHC	Pearson Correlation	-.191	-.113	.071	.087	-.461	-.398	.285	1.000														
	Sig. (2-tailed)	.013	.143	.361	.261	.000	.000	.000															
	N	168	168	168	168	168	168	168	168														
pH	Pearson Correlation	.077	.340	-.383	-.141	.240	-.065	-.317	.147	1.000													
	Sig. (2-tailed)	.319	.000	.000	.068	.002	.404	.000	.058	.													
	N	168	168	168	168	168	168	168	168	168													
E.B	Pearson Correlation	.165	.528	-.302	-.407	.159	-.198	-.285	.265	.667	1.000												
	Sig. (2-tailed)	.032	.000	.000	.000	.040	.010	.000	.001	.000													
	N	168	168	168	168	168	168	168	168	168	168												
NA	Pearson Correlation	.240	.441	-.229	-.356	.325	-.232	-.481	.192	.326	.596	1.000											
	Sig. (2-tailed)	.002	.000	.003	.000	.000	.002	.000	.012	.000	.000	.											

	N	168	168	168	168	168	168	168	168	168	168	168											
K	Pearson Correlation	-.027	.323	-.215	-.229	.091	-.241	-.253	.327	.523	.697	.534	1.000										
	Sig. (2-tailed)	.726	.000	.005	.003	.240	.002	.001	.000	.000	.000	.000											
	N	168	168	168	168	168	168	168	168	168	168	168	168										
Ca	Pearson Correlation	-.114	.232	-.148	-.167	-.141	-.282	-.002	.342	.729	.713	.245	.566	1.000									
	Sig. (2-tailed)	.142	.002	.055	.030	.068	.000	.976	.000	.000	.000	.001	.000										
	N	168	168	168	168	168	168	168	168	168	168	168	168	168									
Mg	Pearson Correlation	.181	.419	-.224	-.331	.194	-.006	-.236	.235	.599	.771	.336	.632	.592	1.000								
	Sig. (2-tailed)	.019	.000	.004	.000	.012	.942	.002	.002	.000	.000	.000	.000	.000									
	N	168	168	168	168	168	168	168	168	168	168	168	168	168	168								
P	Pearson Correlation	.092	.448	-.216	-.371	.210	-.268	-.325	.112	.271	.493	.706	.506	.274	.327	1.000							
	Sig. (2-tailed)	.236	.000	.005	.000	.006	.000	.000	.148	.000	.000	.000	.000	.000	.000	.							
	N	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168							
OC	Pearson Correlation	-.371	.254	-.140	-.199	-.463	-.423	.264	.458	.339	.472	.100	.454	.637	.371	.204	1.000						
	Sig. (2-tailed)	.000	.001	.070	.010	.000	.000	.001	.000	.000	.000	.198	.000	.000	.000	.008							
	N	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168						
T. N.	Pearson Correlation	-.389	-.059	.002	.066	-.435	-.102	422	.115	-.064	-.115	-.416	-.109	.206	-.053	-.275	.523	1.000					
	Sig. (2-tailed)	.000	449	.976	.396	.000	.187	.000	.136	.413	.138	.000	.159	.007	.494	.000	.000						
	N	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168					
C/N	Pearson Correlation	.020	.379	-.161	-.330	.085	-.272	-.253	.257	.269	.507	.635	.545	.272	.344	.642	.382	-.457	1.000				
	Sig. (2-tailed)	.796	.000	.037	.000	.273	.000	.001	.001	.000	.000	.000	.000	.000	.000	.000	.000	.000	.				
	N	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168				
Fe	Pearson Correlation	-.072	-.365	.041	.392	.109	.313	.055	-.322	-.298	-.433	-.315	-.356	-.325	-.403	-.227	-.407	.008	-.423	1.000			
	Sig. (2-tailed)	.351	.000	.602	.000	.158	.000	.479	.000	.000	.000	.000	.000	.000	.000	.003	.000	.918	.000				
	N	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168			
Cu	Pearson Correlation	.320	.212	-.104	-.174	.348	.221	-.294	-.114	.422	.280	.077	.021	.246	.391	-.063	-.079	-.119	-.111	-.113	1.000		
	Sig. (2-tailed)	.000	.006	.178	.024	.000	.004	.000	.142	.000	.000	.320	.787	.001	.000	.420	.308	.123	.152	.146			
	N	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168		
Zn	Pearson Correlation	-.121	.267	-.221	-.159	.108	.092	-.078	.122	.270	.427	.159	.355	.342	.475	.270	.384	.120	.238	-.110	.161	1.000	
	Sig. (2-tailed)	.118	.000	.004	.039	.163	.236	.317	.114	.000	.000	.039	.000	.000	.000	.000	.000	.122	.002	.157	.037		
	N	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	
Mn	Pearson Correlation	-.065	-.075	-.065	.125	.000	.148	.080	.157	.216	.152	-.153	.011	.301	.282	-.084	.317	.353	-.061	.036	.222	.286	1.000
	Sig. (2-tailed)	.402	.335	.401	.107	.998	.055	.301	.042	.005	.049	.047	.888	.000	.000	.279	.000	.000	.429	.645	.004	.000	
	N	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168

Appendix 77

t- test of different organic matter fractions in Vazhachal Forest Division

Parameters	Natural forest		Teak plantations		t- values
	Mean	SE	Mean	SE	
Fats & wax	0.045	0.002	0.025	0.003	5.366
Resin	0.045	0.002	0.023	0.003	6.583
F Sugar	0.036	0.001	0.021	0.001	12.006
Hemi cellulose	0.347	0.009	0.282	0.001	4.568
Cellulose	0.086	0.007	0.055	0.003	4.310
Lignin	1.044	0.002	0.829	0.002	7.532
Protein	0.814	0.002	0.728	0.002	3.355

t- test of different organic matter fractions in Thrissur Forest Division

Parameters	Natural forest		Eucalypts plantations		t- values
	Mean	SE	Mean	SE	
Fats & wax	0.065	0.002	0.031	0.003	9.213
Resin	0.063	0.003	0.124	0.005	-11.722
F Sugar	0.048	0.002	0.030	0.003	5.517
Hemi cellulose	0.511	0.010	0.322	0.009	13.458
Cellulose	0.119	0.002	0.048	0.001	27.139
Lignin	1.491	0.003	0.832	0.002	19.641
Protein	1.142	0.002	0.716	0.002	16.914

Appendix 78

Inter correlation between proximate constituents

		Fats & wax	Resin	Free sugar	Hemi cellulose	Cellulose	Lignin	Protein	Organic carbon
Fats & wax	Pearson Correlation	1.000							
	Sig. (2-tailed)	.0							
	N	20							
Resin	Pearson Correlation	-.002	1.000						
	Sig. (2-tailed)	.994	.0						
	N	20	20						
Free sugar	Pearson Correlation	.957	.144	1.000					
	Sig. (2-tailed)	.000	.546	.0					
	N	20	20	20					
Hemi cellulose	Pearson Correlation	.941	.080	.921	1.000				
	Sig. (2-tailed)	.000	.738	.000	.0				
	N	20	20	20	20				
Cellulose	Pearson Correlation	.934	-.225	.860	.888	1.000			
	Sig. (2-tailed)	.000	.340	.000	.000	.0			
	N	20	20	20	20	20			
Lignin	Pearson Correlation	.956	-.096	.910	.973	.952	1.000		
	Sig. (2-tailed)	.000	.688	.000	.000	.000	.0		
	N	20	20	20	20	20	20		
Protein	Pearson Correlation	.913	-.088	.861	.968	.913	.984	1.000	
	Sig. (2-tailed)	.000	.714	.000	.000	.000	.000	.0	
	N	20	20	20	20	20	20	20	
Organic carbon	Pearson Correlation	.964	.024	.929	.983	.930	.987	.974	1.000
	Sig. (2-tailed)	.000	.920	.000	.000	.000	.000	.000	.0
	N	20	20	20	20	20	20	20	20

** Correlation is significant at the 0.01 level (2-tailed).

Appendix 79

KMO and Bartlett's Test

Natural forest and teak plantations

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0. 677
Bartlett's Test of Sphericity	Approx. Chi-Square	1038.912
	df	171
	Sig.	0.000

Natural forest and Eucalypt plantations

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0. 790
Bartlett's Test of Sphericity	Approx. Chi-Square	855.212
	df	171
	Sig.	0.000

Appendix 80

ANOVA of all factor scores in 0-20cm depth for comparing between age classes of location 1

Variables	Source	df	Sum of Squares	Mean Square	F
Factor 1	Between Age groups	2	8.401	4.201	14.674**
	Error	14	4.008	0.286	
	Total	16	12.409		
Factor 2	Between Age groups	2	5.757	2.878	5.322*
	Error	14	7.572	0.541	
	Total	16	13.328		
Factor 3	Between Age groups	2	6.576	3.288	4.122*
	Error	14	11.168	.798	
	Total	16	17.744		
Factor 4	Between Age groups	2	4.065	2.032	1.946
	Error	14	14.625	1.045	
	Total	16	18.689		
Factor 5	Between Age groups	2	15.702	7.851	15.928**
	Error	14	6.901	0.493	
	Total	16	22.603		

Appendix 81

ANOVA of all factor scores in 20-40cm depth for comparing between age classes of location 1

Variables	Source	df	Sum of Squares	Mean Square	F
Factor 1	Between Age groups	2	4.878	2.439	7.318**
	Error	14	4.666	.333	
	Total	16	9.543		
Factor 2	Between Age groups	2	3.574	1.787	4.493*
	Error	14	5.569	.398	
	Total	16	9.143		
Factor 3	Between Age groups	2	2.542	1.271	5.332*
	Error	14	3.337	.238	
	Total	16	5.879		
Factor 4	Between Age groups	2	5.334	2.667	2.634
	Error	14	14.173	1.012	
	Total	16	19.507		
Factor 5	Between Age groups	2	14.212	7.106	24.353**
	Error	14	4.085	.292	
	Total	16	18.297		

Appendix 82

ANOVA of all factor scores in 40-60cm depth for comparing between age classes of location I

Variables	Source	df	Sum of Squares	Mean Square	F
Factor 1	Between Age groups	2	1.296	.648	2.249
	Error	14	4.035	.288	
	Total	16	5.331		
Factor 2	Between Age groups	2	2.166	1.083	3.467
	Error	14	4.373	.312	
	Total	16	6.539		
Factor 3	Between Age groups	2	.578	.289	.517
	Error	14	7.816	.558	
	Total	16	8.394		
Factor 4	Between Age groups	2	6.067	3.033	1.609
	Error	14	26.385	1.885	
	Total	16	32.451		
Factor 5	Between Age groups	2	11.069	5.535	20.958**
	Error	14	3.697	.264	
	Total	16	14.766		

Appendix 83

ANOVA of all factor scores in 0-20cm depth for comparing between age classes of location II

Variables	Source	df	Sum of Squares	Mean Square	F
Factor 1	Between Age groups	2	2.324	1.162	6.660**
	Error	16	2.792	0.174	
	Total	18	5.115		
Factor 2	Between Age groups	2	13.290	6.645	30.693**
	Error	16	3.464	0.217	
	Total	18	16.754		
Factor 3	Between Age groups	2	1.995	0.997	3.574
	Error	16	4.465	0.279	
	Total	18	6.460		
Factor 4	Between Age groups	2	.485	0.243	.619
	Error	16	6.274	0.392	
	Total	18	6.759		
Factor 5	Between Age groups	2	1.711	0.856	4.457*
	Error	16	3.072	0.192	
	Total	18	4.783		

Appendix 84

ANOVA of all factor scores in 20-40cm depth for comparing between age classes of location II

Variables	Source	df	Sum of Squares	Mean Square	F
Factor 1	Between Age groups	2	2.178	1.089	3.121
	Error	16	5.583	0.349	
	Total	18	7.761		
Factor 2	Between Age groups	2	13.715	6.857	19.432**
	Error	16	5.646	0.353	
	Total	18	19.361		
Factor 3	Between Age groups	2	0.243	0.121	1.069
	Error	16	1.817	0.114	
	Total	18	2.060		
Factor 4	Between Age groups	2	4.276	2.138	5.886*
	Error	16	5.811	0.363	
	Total	18	10.087		
Factor 5	Between Age groups	2	6.466	3.233	7.195**
	Error	16	7.190	0.449	
	Total	18	13.656		

Appendix 85

ANOVA of all factor scores in 40-60cm depth for comparing between age class of location II

Variables	Source	df	Sum of Squares	Mean Square	F
Factor 1	Between Age groups	2	2.213	1.107	3.797*
	Error	16	4.663	0.291	
	Total	18	6.876		
Factor 2	Between Age groups	2	14.507	7.254	21.930**
	Error	16	5.292	0.331	
	Total	18	19.799		
Factor 3	Between Age groups	2	0.959	.479	2.227
	Error	16	3.445	.215	
	Total	18	4.403		
Factor 4	Between Age groups	2	9.399	4.699	9.862**
	Error	16	7.624	0.477	
	Total	18	17.023		
Factor 5	Between Age groups	2	7.770	3.885	7.284**
	Error	16	8.534	0.533	
	Total	18	16.304		

Appendix 86

ANOVA of all factor scores in the 0-20cm depth for comparing between age classes of location III

Variables	Source	df	Sum of Squares	Mean Square	F
Factor 1	Between Age groups	3	23.275	7.758	57.878**
	Error	16	2.145	0.134	
	Total	19	25.419		
Factor 2	Between Age groups	3	7.301	2.434	5.166*
	Error	16	7.537	0.471	
	Total	19	14.838		
Factor 3	Between Age groups	3	14.968	4.989	30.890**
	Error	16	2.584	0.162	
	Total	19	17.552		
Factor 4	Between Age groups	3	3.656	1.219	1.173
	Error	16	16.617	1.039	
	Total	19	20.273		

Appendix 87

ANOVA of all factor scores in 20-40cm depth for comparing between age class of location III

Variables	Source	df	Sum of Squares	Mean Square	F
Factor 1	Between Age groups	3	10.737	3.579	24.953**
	Error	16	2.295	0.143	
	Total	19	13.032		
Factor 2	Between Age groups	3	7.202	2.401	4.714*
	Error	16	8.149	0.509	
	Total	19	15.351		
Factor 3	Between Age groups	3	18.183	6.061	31.953**
	Error	16	3.035	0.190	
	Total	19	21.218		
Factor 4	Between Age groups	3	1.293	0.431	.413
	Error	16	16.690	1.043	
	Total	19	17.983		

Appendix 88

Results of ANOVA of all factor scores in 40-60cm depth for comparing between age class of location III

Variables	Source	df	Sum of Squares	Mean Square	F
Factor 1	Between Age groups	3	3.871	1.290	9.513
	Error	16	2.170	0.136	
	Total	19	6.041		
Factor 2	Between Age groups	3	11.441	3.814	9.641
	Error	16	6.329	0.396	
	Total	19	17.770		
Factor 3	Between Age groups	3	14.427	4.809	18.483
	Error	16	4.163	0.260	
	Total	19	18.590		
Factor 4	Between Age groups	3	3.232	1.077	1.072
	Error	16	16.083	1.005	
	Total	19	19.314		

Appendix 89

Mean score of each factor for location 1

Depth 1

Age class	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
NF	.9347952[a]	-.7704436[a]	.5783418	-3.9811988E-02	-1.6869108
21-30 TP	-.4828570[b]	.3023945[b]	.9454948	.7816199	-1.0049330
31-40 TP	-.6796564[b]	.6021913[b]	1.9928609	-.3890134	.5331649

Depth 2

Age class	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
NF	0.03504183[a]	-1.2123784[a]	-.3029126[a]	-.8531919	-1.7002521[a]
21-30 TP	-1.0150362[b]	-2.9971834E-02[b]	-.4251457[a]	.6072683	-1.4828495E-02[b]
31-40 TP	-1.2076972[b]	-.4827534[ab]	.4159033[b]	-.1428415	.4565010[b]

Depth 3

Age class	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
NF	-.5604370	-1.1839666[a]	-.2589387	-.6710564	-1.0292953[a]
21-30 TP	-1.1894924	-.2702429[b]	-.1873990	.8674237	-.5973442[a]
31-40 TP	-1.1479275	-.5888919[ba]	.1472120	.2885593	.7913544[b]

Mean score of each factor location 2

Depth 1

Age class	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
NF	1.8459140[a]	-.7573618[a]	1.1509797	-3.2989362E-02	.5009676[a]
41-50 TP	1.0904418[b]	.8858991[b]	.4617836	-.4736201	9.929865E-02[ab]
>50 TP	1.0330097[b]	1.2392412[b]	.3935938	-.2555654	-.2253495[b]

Depth 2

Age class	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
NF	.8754310	-1.1120004[a]	-.4199476	-.5594184[a]	1.2074432[a]
41-50 TP	3.039346E-02	.3187267[b]	-.6332751	-.2720850[a]	2.088791E-02[b]
>50 TP	.1649811	.9505620[b]	-.6916461	.5110946[b]	-.1745125[b]

Depth 3

Age class	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
NF	.5645652[a]	-1.2502091[a]	-.6704433	-.6589800[a]	1.6044742[a]
41-50 TP	-.3686711[b]	.2278893[b]	-1.1058040	-.3849715[a]	-.1372767[b]
>50 TP	.1849562[ab]	.8706972[b]	-1.2081146	.8724855[b]	.5356067[b]

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Mean score of each factor for location 3

Depth 1

Age class	Factor 1	Factor 2	Factor 3	Factor 4
N.F	2.4374790[a]	-.3030197[a]	-.8027644[a]	-4.4849432E-02
E II	.6069435[b]	1.0414197[b]	1.2673005[b]	.8740116
E III C	-.2225681[c]	.3921690[a]	-.2570892[c]	-.1821865
E III R	-.1848309[c]	1.2379526[c]	-.8909728[a]	-9.3377243E-02

Depth 2

Age class	Factor 1	Factor 2	Factor 3	Factor 4
N.F	1.0410575[a]	-.9748338[a]	-.5899716[a]	7.830523E-02
E II	-.1708010[b]	-.2863325[a]	1.5881349[b]	-.1605165
E III C	-.9339999[c]	-.1788930[ca]	-.4514538[a]	-.1568052
E III R	-.4880340[bc]	.7129787[cb]	-.7574222[a]	-.6227198

Depth 3

Age class	Factor 1	Factor 2	Factor 3	Factor 4
N.F	2.892596E-02[a]	-1.5409146[a]	.2727876[a]	-.5275156
E II	-.2088743[a]	-.1128235[cd]	1.5838436[b]	.2552938
E III C	-.9814464[b]	-.5297924[bd]	-.3410115[ac]	8.909644E-03
E III R	-.9238513[b]	.5420894[c]	-.6213812[c]	.5714499

NF –Natural forest, TP – Teak plantation,
EII – Eucalypt II[nd] rotation, EIII C – Eucalypt III[rd] rotation coppiced, EIII R - Eucalypt III[rd] rotation replanted

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