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Forest soil characteristics and variability under teak (*Tectona grandis* Linn. F) plantations and natural forests in Ashanti Region, Ghana.

By

Isaac G. Amponsah©

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ABSTRACT

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Keywords: *Tectona grandis* plantations, moist semi-deciduous forest zone, Ghana, soil physico-chemical properties, forest ochrosol.

The variability of forest soil properties and the number of samples required to achieve desired levels of precision for estimation of property means have received little attention in the tropics. Highly variable forest soil properties require more intensive sampling and often have less predictive value for site assessment purposes. The study also compared soils of natural forests and areas converted to teak (*Tectona grandis* Linn. F) plantations (21.3 ± 5.1 years) in the Offinso and Juaso Forest Districts in the Ashanti region, Ghana.

Sites selected for this study were in the moist semi-deciduous forest zone and had nearly identical physiographic characteristics. A simple random sampling procedure was used to obtain soil samples at each site. In each of three natural forest stands and three teak plantations, 16 soil pits were examined and soil samples from the 0-20 (major rooting depth) and 20-40 cm depth were analysed for selected chemical and physical properties.

In the 0-20 cm depth, coefficients of variation varied from 8% (pH) to 72% (available P), and in the 20-40 cm depth from 16% (pH) to 116% (available P) under teak plantations. Similarly, in the 0-20 cm depth coefficients of variation varied from 11% (pH) to 40% (exchangeable K) and in the 20-40 cm depth from 10% (bulk density) to 86% (available P) under natural forests. Under both cover types, more samples were required to estimate means at ±10% allowable error with a confidence level of 95% for chemical properties than for physical properties.

In the 0-20 cm depth bulk density significantly increased (1.17 to 1.30 g cm^{-3}) but soil organic matter (OM) content (13 to 11%), total nitrogen (0.3 to 0.2 %), available phosphorus (4.2 to 1.2 mg kg^{-1}) and exchangeable potassium (0.4 to 0.3 cmol(+)kg^{-1}), calcium (17.0 to 12.4 cmol(+)kg^{-1}), and magnesium (3.8 to 3.2 cmol(+)kg^{-1}) significantly decreased in soils where natural forests were replaced with teak plantations. Similar results also were found for the 20-40 cm soil depth. The higher nutrient contents in soils under the natural forests may have been due to more litter contributions from understorey vegetation observed there. In the teak plantations nutrient leaching losses may have accelerated due to increased mineralisation and the inability of teak to use the increase in available nutrient.

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November 12, 1998

I.G.A

DEDICATION

To

My dear wife Mrs. Eunice Amponsah and my family with love.

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1.0. INTRODUCTION

Ghana's natural forests have been degraded by years of overcutting, fires, and farming activities, to the point that the annual allowable cut cannot meet requirements of the wood industry (Forestry Department 1993). The result is that some industries must be closed to offset the overcutting of the remaining forests. In view of this, the Forestry Department has developed a plantation strategy to obtain a productive plantation estate of up to 200,000 ha within 40 years at an annual planting rate of 5,000 ha to maintain continuous timber export and domestic supply. Furthermore, individuals, communities, Non-Governmental Organisations (NGOs) and timber companies have already embarked on large scale plantations using teak (*Tectona grandis* Linn. F).

With an unprecedented increase in the demand for raw materials for various wood-based industries and the economic benefit of teak, large areas of secondary forests and farmlands in Ghana are being converted into plantations of different species but with special emphasis on teak. However, according to Awuah (1995), although teak is economically valuable, large teak plantations could frustrate Ghana's afforestation programme because there is the risk of endangering indigenous tree species possibly leading to extinction.

Teak is currently regarded as one of the most suitable species for rapid production of large volumes of uniform and desirable quality wood. Introduced into Ghana between 1900 and 1910 by the German administration in the Togo region (FAO/UNEP 1981, Kadambi 1972), the species has been found to be fast growing and adaptable to a wide variety of site conditions in Ghana. Owing to these characteristics, large scale establishment of teak plantations were embarked upon in the 1960's with the assistance of Food and Agriculture Organisation (FAO) of the United Nations and by the early 1970's the rate of planting reached a peak. This reforestation programme was aimed at producing wood to complement the natural forest in meeting the country's long term domestic and export requirements (Prah 1994). In response to this, FAO proposed a national forest plantation estate of 59,000 km^2 starting with planting of 50 km^2 in 1968 (FAO / UNEP 1981). Inventory reports indicate that the current status of Forestry Department's productive plantation estate in the high forest zone is about 15,000 ha. Out of this, teak covers about 10,000 ha. The remaining 5,000 ha is covered by *Gmelina arborea* (Linn) and *Cedrela.* The total area afforested with teak in Ghana might be larger than the area documented by the Forestry Department since this estimate excludes plantations put up by individuals, communities, Non-Governmental Organisations (NGOs) and timber companies like Pioneer Tobacco company, Ashanti Goldfields Limited, Glisksten Limited, and Bibiani Goldmines *etc*. Drechsel and Zech (1994) estimated the total area covered by teak in Ghana to be between 30,000 and 45,000 ha. Thinnings from teak plantations have supported Ghana in its electrification programme over the past six years. Thinnings by the year 2005 are expected to produce about 22,500 pieces of poles and small sawlogs (7500 m^3) annually (Forestry Department 1993, 1994).

Concerns over soil changes under monoculture plantations in general have been repeatedly and increasingly expressed during the last decades yet comparatively few studies have been carried out to elucidate the problem (Lundgren 1978). It is generally agreed that fast growing, short rotation crops may deplete soil nutrients and that tree planting significantly affects physical and chemical properties of soil, and consequently affects ecosystem dynamics (Aborisade and Aweto 1990, Alexander *et al.* 1981, Prasad *et al.* 1985).

Tree species and forest types vary in their site requirements and in capacity to absorb soil nutrients. Therefore, differences in vegetation type will produce differences in soil properties. In Southern Nigeria, teak has been found to cause significant nutrient loss at site through nutrient immobilisation in the standing biomass that led to depletion of nutrients from the soil (Aborisade and Aweto 1990), particularly during tree harvesting. Teak harvest has been found to result in considerable loss of calcium (Ca) and organic matter (OM) (Hase and Foelester 1983), and soil leaching and erosion have led to losses in potassium (K), sulphur (S) and nitrogen (N) (Bhoumik and Totey 1990, George and Varghese 1992, Mongia and Bandyopadhyay 1992, Nwoboshi 1984). Further, various soil characteristics important for teak growth and distribution have been studied by many researchers but complete information across different climatic, physiographic and edaphic conditions is lacking. Quantitative data are required to test the hypothesis of soil deterioration by teak plantations (Jose and Koshy 1972, Seth and Yadav 1959, Yadav and Sharma 1968).

An understanding of soil variability is essential in studies of relationships between tree growth and soil properties. This is particularly true for assessments of capacity of forest sites, in which timber production is predicted from known relationships between tree growth and site attributes (Blyth and Macleod 1978). The forest soil is the principal location for nutrient uptake in forest ecosystems of tropical climatic zones and should receive, therefore, special attention when assessing nutrient supply, nutrient availability, nutrient cycling and forest growth. According to Hedley and Kang (1972), one major problem in quantifying the ecological role of forest soil in terms of averages in the tropics, particularly on recently cleared land, is the high degree of soil variability which results in uneven crop growth. It has also been observed that high spatial variability of soil physical and chemical properties limits accurate assessment of forest soils (Mroz and Reed 1991) and forest land classification which is an important step in the development of intensive forest management programmes. In addition, such highly variable soil factors are also of little predictive value for studying tree growth and assessing factors such as soil degradation. Although little is known about variability of forest soil properties in Ghana, it is hypothesised that they would be probably less than those of the Boreal and Temperate forest zones. This is in part because of the geology, topography, drainage and residually developed soils under Ghanaian forests in the moist Semi-deciduous zones. In order to obtain information on soil variability in Ghana; some investigations were carried out under teak plantations and natural forests in the Ashanti region of Ghana, the results of which are reported in this thesis.

Although the afforestation programme in Ghana has been continuing for some years, information on interactions between tree species and soil conditions is incomplete and fragmentary. Furthermore, the spatial variability of forest soils and the number of samples required to achieve desired levels of precision for estimation of property means have received little attention in Ghana. Under these circumstances, it is desirable to investigate forest soil variability, and the nature and extent of teak plantation effects on soil properties so that appropriate long-term management strategies can be formulated. This study was carried out, to quantify the variability of physical and chemical properties of soils under teak plantations and adjoining natural forests in the Ashanti region of Ghana. The specific objectives are:

1. To determine the number of samples required to estimate the mean values of commonly measured soil properties.
2. To compare selected soil properties under teak plantations and adjoining natural forests.

It is hoped that the results of the study would provide a data base of forest soil variability for pre-plantation site assessment and soil degradation research.

2.0. LITERATURE REVIEW

2.1.0. SILVICULTURAL CHARACTERISTICS OF TEAK

2.1.1. General Description Of Teak (*Tectona grandis* Linn. F)

A member of the *Verbenaceae* family, *Tectona grandis* is a deciduous tree with variable size and form according to locality and conditions of growth. In favourable localities, teak may reach a height of 40-45 m, with a bole up to 25-27 m. Heights of 35 m and dbh. of 70 cm in 46 year-old teak have been reported in Madhya Pradesh, India (Bhoumik and Totey, 1990). Diameter at breast height (dbh) typically range between 1.8 and 2.4 m (Borota 1991, Farmer 1972, Kadambi 1972). In April 1996, the largest standing teak tree in Baw Forest Reserve of Myanmar had a dbh of 2.4 m and height 46 m (Centeno 1997). In drier regions, teak is smaller. At older ages, teak becomes moderately fluted and buttressed at the base. Leaves of teak are large, opposite and decussate in arrangement (Borota 1991, Farmer 1972, Hedegart 1976). The species develops thick tap root system which may persist or disappear; strong lateral roots may also be formed. Exposed teak suffers from wind, which causes branching but this may be minimised if protected with shelterbelts. Seedlings and coppices of teak are very sensitive to abnormal drought, fire, drainage and frost. Teak produces vigorous shoots when coppiced (Borota 1991, Kadambi 1972, Keogh 1987, White 1991).

2.1.2. Teak Wood And Uses

Teak has excellent wood properties making it one of the valuable multipurpose timbers of the world (Keogh 1987). It is resistant to termites, fungi and adverse weather conditions. Teak seasons without splitting, cracking, warping, or physically altering shape and is employed in a wide range of end uses such as exterior and interior joinery, window and door frames, flooring, cabinet work, garden furniture, decking, boat building, bridges, railway carriages, sleepers *etc.* (Borota 1991, Keogh 1987, White 1991).

In Ghana, under the Forest Resource Management Project which began in 1989, the Rural Forestry Division of the Forestry Department initiated numerous community teak plantations. Communities are now benefiting from teak plantations in the form of poles for construction, yam stakes, rafters and fencing posts.

2.1.3. Distribution

Teak is indigenous through the greater part of Myanmar, Indian Peninsula, western parts of Thailand and Indo-China from about latitude 12° to 25° North (Figure 1) and from about longitude 73° to 104° East (Beard 1943, Parameswarappa 1995, Street 1962, White 1991). Centuries ago it was introduced into Java and some of the smaller Islands of the Indonesian Archipelago (Parameswarappa 1995, Street 1962, White 1991) and later into the Philippines. Today, the species is naturalised in these countries (Beard 1943). Long established teak plantations now extend from 28° N to 18° S in countries like Sri Lanka, Malaysia, Pakistan, Indonesia, Zambia, Tanzania, Uganda, Côte d'Ivore, Ghana, Togo, Nigeria, West Indies, Honduras Trinidad, Jamaica, Argentina and Panama (Parameswarappa 1995, White 1991). Currently, teak is being planted on the Savanna woodland and on parts of the High Forest ecoregion of Ghana. Indications are that teak growth is better in the moister High Forest Zone than Savanna woodland.

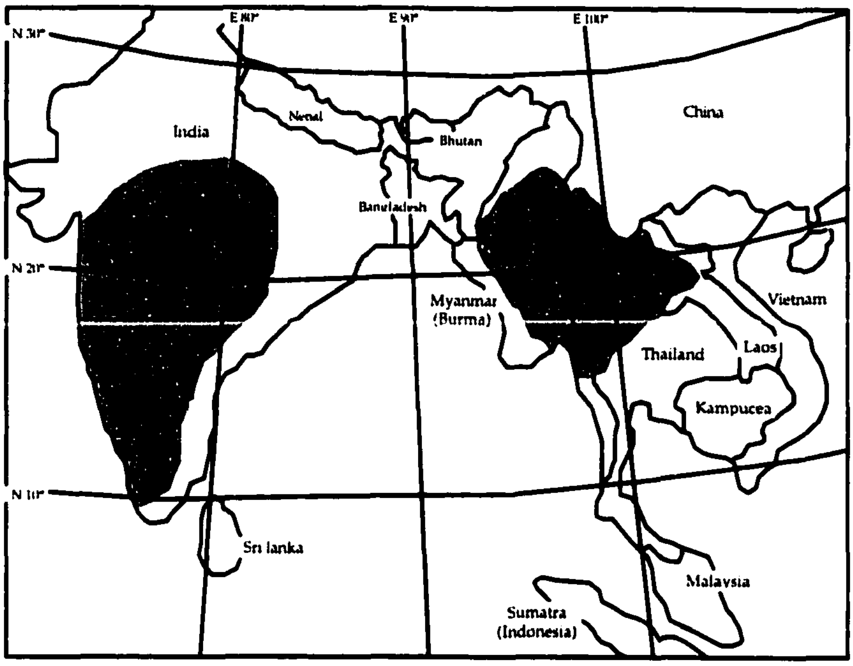


Figure 1. Natural range of teak in Asia (adapted from Weaver 1993).

2.1.4. Habitat And Climatic Requirements Of Teak

The distribution of teak is largely determined by climate, geology and soil (Parameswarappa 1995). The rate of growth and the quality of teak from plantations largely depends on the type and quality of planting stock, the physical and chemical characteristics of the soil, environmental conditions and management techniques. Teak grows and survives a wide range of climatic conditions but thrives best in fairly moist warm tropical climates (Kadambi 1972, Street 1962). Much of teak's natural range is characterised by monsoon climates with rainfall between 1,300 and 2,500 mm per year and a dry season lasting 2 to 5 months (Salazar *et al.* 1974). Optimum rainfall for teak is between 1,500 and 2,000 mm per year. Teak endures rainfall as high as 4,000 mm in Bangladesh to as low as 600 mm in Togo. However, prolonged droughts in India have killed both trees and coppice sprouts (Ryan 1982).

The species tolerates wide variations in temperature, from 2 to 48° C (Troup 1921). In the west coast of India, the optimum climate for teak growth has a temperature range between 16° and 40° C. Teak may extend into regions of slight frost, but throughout almost all of its range, teak has not been found in frost regions (Kadambi 1972, White 1991).

Teak is intolerant to shade and requires full sunlight (Borota 1991, White 1991). The species establishes best on terrain cleared of competing vegetation. It is unable to stand much competition from other plant species or from trees of the same species. The crown of teak requires freedom on all sides for proper development. However, in very hot and dry areas, teak seedlings and saplings benefit from protection against the hot afternoon sun. In Madhya Pradesh (Kasoa-ard 1981), teak saplings in the shade of bamboo, exhibited slow growth. However, teak growth increased when bamboo were removed and full overhead light was restored. Photoperiod also appears to have minor effect on its growth and development (Kasoa-ard 1981).

2.1.5. Site and Nutrient Requirements of Teak

Teak establishes itself on a variety of geological formations and soils (Hedegart 1976, Kadambi 1972, Seth and Yadav 1959). It grows best on deep, porous, fertile, well drained, alluvial soil with neutral or acidic pH (Kadambi 1972, Salazar *et al.* 1974, Walterson 1971). In the Indian Peninsula, the species grows on soils derived from sandstones, but becomes stunted on quartzite or hard metamorphosed sandstone which weather slowly. Teak also grows on soils derived from granite, gneiss, schist and other metamorphic rocks. The species also does well on limestone that has disintegrated to form a deep loam. On hard limestone, where the soil is shallow, teak growth is poor. As a rule the species is not found frequently on lateritic soils (Borata 1991, Keogh 1987, Ryan 1982). The species requires fertile soils for best growth (Parameswarappa 1995, Salazar *et al.* 1974), notably those rich in Ca and Mg (White 1991). Nitrogen nutrition, rooting depth and precipitation are the most important variables influencing teak growth in West Africa (Drechsel and Zech 1994).

The distribution of nutrients in teak has been the subject of numerous investigations (Weaver 1993). The percentage of nutrients in 1-year-old teak seedlings decreases in the following order N > Na > Ca > K > P (Lalman 1985). Nutrient concentrations were highest in leaves decreasing in stem and roots. The seedling nutrient composition increased 8 to 9 months, after which N, P, and K decreased remarkably, and Ca and Na decreased slightly. Besides N, Drechsel and Zech (1994) also believed P and Ca to influence teak growth. Samples of 40 of the best quality teak trees representing the age diameter range attained during the first 15 years of plantation establishment in Nigeria's Gambari Forest Reserve were analysed for N, P, K, Ca and Mg (Nwoboshi 1984). This study indicated the teak plantation had an above ground dry weight of 592,000 kg ha^{-1} and contained 2,980 kg ha^{-1} of K, 2,228 kg ha^{-1} Ca, 1,788 kg ha^{-1} N, 447 kg ha^{-1} P, and 377 kg ha^{-1} Mg. Further, the minimum annual nutrient requirement at age 15, in kg ha^{-1}, were 556 of K, 328 of N, 357 of Ca, 76 of P, and 62 of Mg. The relative amount of element found in foliage decreased with age, whereas that in the branches and trunk increased with age. Nutrients taken up by teak are considerably greater than that required for a pine plantation in the same area or in a 49 years old secondary forest in Ghana (Nwoboshi 1984). This indicates that teak's nutrient use is high compared to some other forest species.

2.2. PROPAGATION AND MANAGEMENT

Seeding of teak has in the most part, given unsatisfactory results because of unfavourable environmental conditions during early stages of establishments. Presently most teak plantations are established by planting stumps which are easier to plant and provide more rapid and vigorous growth (Weaver 1993). A stump plant is produced in nurseries by stump cuttings (about 5 cm above ground or above the root collar) or root cutting of 10-20 cm. The stump is planted into prepared ground at the beginning of the rainy season (Borota 1991). Spacing of plants depends on management objectives and site characteristics. For example, on sloping terrain, wider spacing (3.5 by 3.5 m) have been suggested to encourage ground cover and to avoid soil erosion (Weaver 1993). Despite the success of the stump method, planting stock is still produced from seeds in spite of the quantitatively limited and late seed production, low germination rates, and substantial variability in growth and wood quality (White 1991).

A viable option for the production of high volumes of quality teak wood is to establish pure plantations on well prepared and well drained soils and to manage them to reach average height before flowering sets in. Normally 1,200 to 1,600 plants per hectare are used, with closure of canopy commonly taking place between the third and fourth year (Centeno 1997, Kadambi 1972). A common strategy to grow long knot-free boles is to keep the stand closed and at high density during the first year of development when rapid height growth occurs. This keeps crowns small and consequently limits the size of the branches (Centeno 1997).

The age at which first thinning is done is determined by the dominant height, which is in turn determined by site quality (Centeno 1997). On best site classes, first thinning might be possible when the dominant height reaches 9.5 m and second thinning when the dominant height reaches 17 -18 m. When thinnings are light, only small temporary canopy gaps are created and total production per hectare will not deviate significantly from the carrying capacity of the site. If thinning occurs too late, the stand is affected by stagnation with loss of growth potential. However, if the stand is thinned too early or too heavily, the trees tend to produce more side branches and epicomic shoots (Centeno 1997). Lowe (1976) noted that a 10-15 year delay of thinning may not affect the growth potential of the final tree crop. Keogh (1987) noted that if thinning is delayed beyond 10 years, the final tree crop would be unable to respond fully to later thinnings. Based on the assessment of economic and silvicultural considerations, a rotation of 25-45 years may at present be considered as the optimum cycle to achieve viable financial returns and the production of market quality timber (Centeno 1997). Weaver (1993) noted that pure teak plantations have rotations 50-80 years, whereas in areas where the species grows in mixed stands, rotation is about 70-80 years. When managed under coppice systems, teak rotations ranges from 40-60 years. Fifty-year Indian yield tables allow for 80-year rotations (FAO 1956). Timber volume predicted from yield tables on site class at 80 years, was 340 m^3 per hectare (Borota 1991). Borota (1991) and Keogh (1987) noted that the rotation for obtaining high quality logs is usually around 70 to 80 years.

In Asia, teak trees are allowed to develop for 60 years or more before harvesting. At such ages, the mean annual increment (MAI) may vary from three to 10 m^3 ha^{-1} yr^{-1}. According to Parameswarappa (1995), the world's fastest teak growth is in plantations at Chittagong District (Bangladesh) at Kaptai. Trees 21 years old had an average height of 29.3 m and an average diameter of 30.0 cm. The stem timber volume was 34.09 m^3 and small timber volume was 8.66 m^3 per acre. In tropical America, most teak plantations are managed with short rotations, usually 20 to 30 years. The MAI at these ages varies from 10 to 20 m^3 ha^{-1}.

Although fire is often an important component for the regeneration of teak within its natural range fire tends to weaken teak and causes unwanted side-effects, especially after the fourth year of establishment (Keogh 1987). Very young stands may recover quickly by producing vigorous coppice shoots. In general, older stands of teak are more resistant to fire. However, it is advisable to provide fire protection during each dry season. From the fourth year until the time when the bark is thick enough to withstand high temperatures, teak may be killed and stripped in spots thereby rendering the wood susceptible to fungal attack. In the drier forests, fire may kill young trees and may damage large trees. Fire is also associated with epicomic branching. Furthermore, fire also accelerates erosion under teak by removing undergrowth and protective litter layers (Keogh 1987, White 1991) and may result in loss of nutrients. Repeated fire may also reduce site potential, thereby causing a decrease in growth rate. For example, in Burma, Trinidad, and Thailand, soil erosion in pure teak plantations has been attributed to the burning of undergrowth (Kadambi 1972). Balagopalan (1987) studied the effect of fire on soil properties in different forests of Kulamav, Kerela, India and concluded that fire had no effect on soil texture.

2.3. NEED FOR PLANTATION ESTABLISHMENT

Plantations in the humid regions of Africa are planted primarily with exotics- *Eucalyptus spp., Pinus spp., Tectona grandis, Gmelina, Cedrela and Acacia* (Evans 1996). In the humid regions of Africa, the area under native species plantation is less than 15 per cent. In Africa over 80 native tree species have been tested in various trials, of which more than 60 have been tested in the Côte d'Ivore, west of Ghana (FAO 1993). However in Ghana, as in many other countries in the region, only plantations of exotic tree species have succeeded despite substantial effort committed toward the establishment of native species plantations (Cobbinah 1997). A plausible explanation for widespread failure of native species in plantations is the high incidence of insects and disease pests that develop in these monocultural plantations and a failure to recognise the important ecological characteristics of species selected for plantation (Cobbinah 1997).

According to FAO projections (FAO 1993), global wood consumption is estimated at 3.5 billion m^3 y^{-1} in 1990, and is expected to reach 5.1 billion m^3 y^{-1} by 2010. According to Evans (1996), industrial wood consumption is expected to rise to 2,600 million m^3 annually by the year 2030. Evans (1996) further noted that, at a consumption level of 4,000 million m^3 y^{-1} it would take 75 years to use up the worlds' resources of wood; this assumes no increment, no regeneration, and no planting at all. Evans (1996) attributed the main causes of forest destruction to clearance for agriculture, intensive logging for veneer, sawn timber and more recently for chipboard, exploitation for charcoal and fuelwood. The consequences of forest destruction are deforestation and resultant land degradation problems. In Ghana, the total wood utilized for fuel wood for an estimated population of 15 million in 1990 was million 13.9 m^3 y^{-1} of which charcoal accounted for 6.53 million m^3 (47% of the fuel wood consumption) (World Bank 1988). The World Bank (1988) projected that by the year 2000 the charcoal component would rise to 10.77 million m^3 y^{-1}(52 %). The annual total wood volume currently used for timber and fuel in Ghana are together estimated to be 16.4 m^3(Chachu 1997). By the year 2020, Ghana's population is expected to reach at least 30 million, and corresponding fuel wood consumption is projected to reach 28.8 million cubic m. This trend is equally significant in Latin America and the Caribbean: in Brazil, for example, where about 80 per cent of the planted forests of tropical Latin America are located, the consumption of wood is estimated to be 281 million m^3 y^{-1}, of which 75 million m^3 y^{-1} are supplied by planted forests (Reis 1997).

The need to minimize deforestation effects through establishment of forest from native and exotic species has become apparent in recent investigations. Presently, money is being invested in search of plant species with different potential as well as the development of adequate technologies for the proper cultivation of such species to gain higher yields in less time. This would help satisfy the increasing demands for forest products and to decrease the destruction processes of natural resources.

The increased rate of plantation establishment is for socio-economic and ecological gains. Socio-economic benefits include job creation, income generation, raw materials for timber industries, charcoal for iron and steel industries *etc.* Ecological benefits include maintenance of soil fertility, watershed protection, shelterbelts, windbreaks *etc.* Further plantation forest can contribute toward reducing the world's wood deficit (Reis 1997).

2.4. INFLUENCE OF TEAK ON SOIL CHEMICAL PROPERTIES

In the tropics, there is a general belief that plantations and natural forests have different effects on the ecosystem. Studies conducted by Prasad *et al.* (1985), Singh and Totey (1985), Mongia and Bandyopadhyay (1992) indicated that organic matter (OM) content, cation exchange capacity (CEC), and exchangeable cations are higher in soils under natural forests and mixed plantations than in soils under monocultures. It is also believed that plantation forestry may result in soil compaction and nutrient immobilization in the standing biomass (Aborisade and Aweto 1990, George and Varghese 1992). Mongia and Bandayopadhyay (1992) compared the changes occurring in soils of tropical forests after clearfelling for high value plantation crops of *Pterocarpus dalbergiodes* (Padauk), *Tectona grandis* (Teak), *Hevea brasiliensis* (Rubber) and *Elaeis guinensis* (red oilpalm). Their results indicated a decline in OM, P and available K when the forest was removed for raising plantation crops. Also $CaCO_3$ content was completely lost from the soil profiles. Similarly, in South Andaman, India, Mongia and Bandayopadhyay (1994) soil N, P, K, organic carbon (C) and pH were found to be lower under teak, rubber, red oilpalm, and padauk plantations than under natural forests. In Ethiopia, Michelsen *et al.* (1993) observed lower OM and nutrient content in soils under two exotic plantation species (*Cupresus lusitanica* and *Eucalyptus globulus*) compared to soils under *Juniperus procera* and natural forest.

Conversely, in India, Krishnakumar *et al.* (1991) compared the ecological impacts of *Hevea brasiliensis, Tectona grandis* plantations and natural forests on soil properties, nutrient enrichment, understorey vegetation and biomass recycling. The study indicated all stand types retained a high OM input that helped enrich the soils. Although teak had the highest OM content in the surface layer, depletion of OM with depth was highest for teak and less for natural forests. The depletion pattern for rubber was close to that of natural forests.

A study under different climatic conditions in Western Ghats, India, revealed that sites with very high densities of teak were characterised by higher organic carbon as well as higher exchangeable Ca and CEC (Singh *et al.* 1986). In Nigeria, Totey *et al.* (1986) compared the changes of soil chemical properties under three different vegetation covers, mixedwood forest, *Eucalyptus* and teak plantations. The study indicated that the rate of weathering, ratio of clay to non-clay fractions, OM, CEC, and exchangeable Ca and Mg were higher under teak cover than under eucalyptus and mixed forest. They attributed the higher CEC under teak to a higher level of soil OM. Higher available Ca and Mg were also attributed to the incorporation and decomposition of teak leaf litter rich in Ca and Mg (Hosur and Dasog 1995). Marquez *et al.* (1993) studied the effect of teak chronosequence (2, 7 and 12 years) on soil properties in the Ticoporo forest Reserve. They observed that Ca and Mg content, pH and CEC were significantly higher in soils of a 12 year-old plantation as compared to two and seven year old plantations. However, available soil P concentration showed a significant decline with plantation age. They attributed these differences to the possibility that older teak trees could take nutrients more efficiently from deeper soil horizons and recycle nutrients to the soil surface as leaf litter.

Hase and Foelster (1983) assessed the potential impact of the removal of teak plantations on the nutrient status of young alluvial soils in the Venezuela. The calculated nutrient budgets suggested that base depletion after tree removal would lead to a reduction in teak productivity on productive sites located away from rivers. Soils situated on low topographic positions near rivers, however, could withstand continued harvest because nutrients lost would be replaced by ground water inputs. However, research on long-term influences of pure teak plantations on soil properties are incomplete and fragmentary (Jose and Koshy 1972, Yadav and Sharma 1968).

In Ghana, chemical properties of soil were compared under two distinct forest covers (logged native forest, and teak plantations) at three different forest reserves (Bosomoa, Tain

II and Yaya) in Ghana (Salifu 1997). Within the Bosomoa and Yaya locations, N, Mg and OM concentrations in the surface soil horizons were significantly higher under logged forest than under teak plantations. Phosphorus and K concentrations were also significantly higher under logged forest at Bosomoa. Similarly, there were less differences in total nutrients in soils under adjacent logged forest compared to teak plantations in the Bosomoa and the Yaya locations. Higher nutrient concentrations and contents in soils under logged forests were due to more undergrowth, litter and organic matter under logged forest. Higher nutrients under the logged forest may also be due to a lesser demand for these nutrients by tree species in these forests. Lower soil macro-nutrient contents in soils under teak may have been due to lower organic matter content under teak cover or associated with higher nutrient demand immobilization by teak.

2.5. INFLUENCE OF TEAK ON SOIL PHYSICAL PROPERTIES

Pure teak stands have also been associated with physical soil deterioration such as erosion (Centeno 1997). However, there is limited conclusive evidence in this regard (Brandis 1921, Centeno 1997) except when teak is planted on steep slopes where there is limited undergrowth or where excessive burning has taken place (Centeno 1997, Griffith 1938, Manning 1941). According to Laurie and Griffith (1942) surface soil under teak plantations sometimes hardens, decreasing aeration and increasing soil erosion. Salifu 1997 noted, higher surface soil horizon bulk densities (Dbs) were observed under teak plantation (1.33 g cm^{-3}) than under the native logged forest. However, similar studies by Laurie and Griffith (1942) under other pure teak plantations in India, did not indicate significant soil deterioration. Laurie and Griffith (1942) concluded that faulty planting techniques and under-thinning were at least partially responsible for the above changes in soils under pure teak plantations. Studies by Bell (1973), Chunkao *et al.* (1976), Karunakaran (1984) and Kushalappa (1987) have shown that soil erosion and sediment yields were higher under teak plantations than other cover types due to heavy grazing pressures and repeated fires.

Soil bulk density (Db) has been found to increase under teak plantation management but not under virgin forests (Mongia and Bandayopadhyay 1992). The high Db was attributed to loss of OM under teak as compared to natural forest. Aborisade and Aweto (1990), Kadamdi (1972), Mongia and Bandayopadhyay (1992) observed that establishment of large scale teak plantations leads to soil deterioration through increased erosion, soil compaction and consequent decrease in aeration. In Kerala, India, Jose and Koshy (1972) studied the morphological, physical and chemical characteristics of soils as influenced by teak. Soil profiles beneath a natural forest and teak plantations of one, 15, 30, 60, and 120 years were compared. Organic matter content in the plantation correlated with the age of the stand. They observed that soils beneath teak plantations less than 30 years old had higher Dbs, lower amount of pore space and water holding capacity than older plantations and natural forests, indicating that physical conditions deteriorated as the teak plantation got older.

2.6. RELATIONSHIPS BETWEEN BULK DENSITY AND SOIL PROPERTIES

A knowledge of Bulk density (Db) is of utmost importance in determination of nutrient content and other physical and chemical properties of forest soils. Values of Db are necessary to convert laboratory measurements of soil nutrient concentrations, exchange capacities, water contents, and biological populations from concentration to a mass basis (Federer *et al.* 1993). Bulk density is an important soil physical property that can directly or indirectly affect plant growth. Bulk density is an important mass (weight) measurement of soils and is affected primarily by texture and structure (Brady and Weil 1996). Bulk density is defined as the mass (weight) of a unit volume of oven dry soil at 105° C. This volume includes solids and pores. Thus, Db is an indirect measure of the total pore space in the soil since Db relates to the combined volumes of solids and pore spaces, soils with a high proportion of pore spaces to solids have lower Db than those that are more compact and have less pore spaces. Consequently, any factor that influence pore space affects Db.

Bulk density and total pore space are readily altered by tillage operations, and other disturbances such as scarification and compaction by heavy equipment at harvest. Bulk density of soils is closely correlated with porosity and in turn, with water infiltration capacity and the degree of aeration. In general, coarse fragments create larger pore spaces in soil volume and may result in a lower Db when calculation is based on coarse fragment less than 2 mm.

Increased aggregation of a particular soil will result in a corresponding increase in total pore space, and the weight per unit volume or Db of the soil will decrease. The Dbs of clay, clay loam, and silt loam surface soils normally range from 1.0 Mg m^{-3} to as high as 1.6 Mg m^{-3}, depending on soil conditions. A variation from 1.2 to 1.8 Mg m^{-3} may be found in sands and sandy loams (Brady and Weil 1996). These general trends apply until coarse fragment content of the soil become significant.

Bulk density can be determined by taking a natural structural aggregate from the soil and by means of a series of weighing in air and in kerosene Db, real density, porosity and water volumes of the aggregates may be calculated (Rennie 1957). Gamma ray attenuation has also been used for measuring both water content and Db in soil (Gurr 1962) but the equipment is relatively elaborate and expensive. The most common method used is the sample cylinder which is simple and convenient (Armson 1977). This method has problems of unknown compaction of sample, difficulty or sampling soils with high coarse fragment level or root content (Federer *et al.* 1993), and poor measurement due to samples falling apart when cylinder is extracted from the soil profile.

In view of the difficulties involved in determining Db, several researchers have developed equations to predict bulk densities of soils based on one or two soil properties. Ball (1964) observed that Db is closely related to OM fractions which can easily be determined by loss on ignition (Adams 1973). Ball (1964) observed that Db tends to decrease as mineral soil OM increases, particularly in forest soils, which tend to be high in organic matter and in aggregate stability near the surface. Curtis and Post (1964) developed an empirical regression of log Db on log OM (loss on ignition) for stony and sandy loam soils in the northeastern United States. This relationship was curvilinear and valid for O, A, E, and B horizons of Vermont forest soils. Federer (1983) and Huntington *et al.* (1989) obtained very similar equations. Huntington *et al.* (1989) concluded that their relationship between Db and OM in the mineral soil for New England and that of Federer (1983) support the use of organic matter to obtain estimates of Db for use in the calculation of soil carbon pools. Jeffrey (1970) suggested that the relationship between OM and Db might be universal. In California, Alexander (1980) observed that the square root of organic carbon was the best predictor of Db in both upland and alluvial groups of soils, but the orders of importance of the other independent variables differed from one group to the other. Federer *et al.* (1993) observed that Db of forest soils in New England were closely and inversely related to the organic fraction of the soil. Rawls (1983) proposed a method for predicting Db of natural undisturbed soils based on the percentages of sand, clay, and OM and concluded that the method could be useful for predicting Db when only particle size information is available and for predicting the effect OM had on Db.

In Ghana, regression models for Db of soils under teak cover were developed using OM, particle size distribution and pH. Significant linear relationships were found between Db, OM, clay, silt, volume of coarse fragments and pH (Salifu 1997)

2.7. VARIABILITY OF SOIL NUTRIENTS

Soil variability, particularly on recently cleared land is a major problem in conducting field experimentation in the Tropics (Hedley and Kang 1972). Accurate assessment of forest soil properties is often difficult because of high variability (Mroz and Reed 1991). When interpreting the significance of numerical data describing the properties of soil samples on a survey basis, it is essential to know the expected variability and confidence limits, not only of analytical methods, but also of the natural variations found in the field (Bracewell *et al.* 1979). In Ghana, data regarding variability of chemical and physical properties of forest soils are meager in comparison to information available on the influence of these properties on plant growth.

Temporal variation in soil nutrient level has been well documented (Anderson and Tiedemann 1970, Gupta and Rorison 1975, Davy and Taylor 1974). Such variation is usually controlled by either timing sampling to coincide with climate or phenological events or by increasing sampling frequency. Spatial variability is also well documented for non tropical soils with fairly large differences in variability among individual nutrients even when samples are stratified by horizons (Mroz and Reed 1991).

Natural variation for a wide range of soil properties has been found to be surprisingly large (Table 1). In a review by Beckett and Webster (1971) coefficients of variation (CV) of 35 and 58% for OM and exchangeable cation contents, respectively, were found within topsoil of a given soil series. Blyth and Macleod (1978) noted that most useful properties for characterizing a forest site are those whose variability remains low over fairly extensive areas. Highly variable soil factors are of little predictive value for studying tree growth (Blyth and Macleod 1978) and assessing factors such as soil degradation.

Mader (1963), studying the soil variability of some forest sites, found that the CV for most soil properties tend to be higher when quantities were low, and suggested that the cause may have been greater analytical error with small amounts. Hemingway (1955) also reported that lower levels of nutrients tend to show higher variation relative to their means. Mader (1963) found that the CV values for total profiles were either considerably less than, or identical to those from the individual A and B horizons.

The spatial pattern of soil heterogeneity, laterally and in depth, influences the effectiveness of predictions based on samples bulked from an area, no matter how intensively the area is sampled (Shiue *et al.* 1957). Cameron *et al.* (1971) found that soil samples taken at the 15-30 cm and 30-61 cm depth showed greater CV in N and P than did samples from 0-15 cm depth. However, samples composed of the 0-30 cm and 0-60 cm depth were similar to the 0-15 cm depth variability. They caution that the interpretation of complementary effects for N and P should be done with great care as both decrease substantially with depth and noted that this accounted for the high CV at lower depth.

able 1. Summary of soil physical and chemical means, standard deviations (SD), standard errors (SE) coefficients of variation (CV), sample size (n) and estimated number of samples required (N).

Author	Location	Cover Type	Soil Type	Variable	Units	Mean	SD	SE	CV%	n	N
Grier and McColl (1971)	W Washington	Douglas Fir	Forest Floor	Ca	ppm	8,615.6		211.8		144	15
			Forest Floor	Mg	ppm	1,363.5		66.6		144	57
			Forest Floor	K	ppm	1,914.0		47.4		144	15
			Forest Floor	N	%	1.0		0.0		45	6
			Forest Floor	pH		5.1		0.0		144	3
			A	pH		5.0		0.0		144	3
			B	pH		5.5		0.0		144	3
Arp and Krause (1982)	New Brunswick	Spruce -Fir (fertilized)	Forest Floor	Mineral-N	ppm	503.5	503.2		100	98	
			Forest Floor	Mineral-N	kg ha^{-1}	29.1	33.3		136	98	
Arp and Krause (1984)	New Brunswick	Spruce -Fir (unfertilized)	Forest Floor	pH		3.4	0.2		6	98	1
			Forest Floor	NO_3-N	ppm	4.5	8.0		178	98	1242
			Forest Floor	Extr. P (field moist)	ppm	10.4	7.1		68	98	181
			Forest Floor	Extr. P (dry, 60°C)	ppm	50.3	14.3		28	98	31
			Forest Floor	Extr. P (dry, 105°C)	ppm	162.0	50.0		31	98	38
			Forest Floor	Extr. Mg	ppm	41.5	12.3		30	98	35
			Forest Floor	Extr. K	ppm	266.0	117.0		44	98	76
			Forest Floor	Extr. Ca	ppm	318.0	106.0		33	98	43
Quesnel and Lavkulich (1980)	Port Hardy, B.C.		LF	Total N	%	0.9			10		1
			H	Total N	%	0.8			13		1
			LF	Total C	%	49.4			3		6
			H	Total C	%	48.3			3		8
			LF	Ca	meq 100 g^{-1}	16.5			29		39
			H	Ca	meq 100 g^{-1}	13.7			47		103
			LF	Mg	meq 100 g^{-1}	7.7			19		17
			H	Mg	meq 100 g^{-1}	8.3			28		36
			LF	K	meq 100 g^{-1}	3.4			28		36
			H	K	meq 100 g^{-1}	2.2			34		53
			LF	Na	meq 100 g^{-1}	1.3			20		20
			H	Na	meq 100 g^{-1}	1.3			18		16
			LF	pH		3.8			3		1
			H	pH		3.7			4		1
Bracewell *et al.* (1979)	Aberdeen, Scotland		Iron Podzol A2	Carbon	%	4.6			34		
			Iron Podzol A2	N	%	0.5			24		
			Iron Podzol A2	pH (H2O)		4.0			7		
			Iron Podzol A2	pH (CaCl2)		3.3			11		
			Iron Podzol A2	Exch. Ca	meq 100 g^{-1}	0.3			50		
			Iron Podzol A2	Exch. Mg	meq 100 g^{-1}	0.2			74		
			Iron Podzol A2	Exch. Na	meq 100 g^{-1}	0.2			49		
			Iron Podzol A2	Exch. K	meq 100 g^{-1}	0.1			31		
			Iron Podzol A2	Total P	mg 100 g^{-1}	61.5			36		

Table 1. continued

Author	Location	Cover Type	Soil Type	Variable	Units	Mean	SD	SE	CV%	n	N
Mader (1963)	Massachusetts	Red pine plantation	F	OM	%	82.5		6.8	12		
			A	OM	%	7.4		1.2	22		
			B	OM	%	3.8		0.7	24		
			A	N	%	0.2		0.0	18		
			B	N	%	0.1		0.0	34		
			A	Db	g cm^{-3}	1.0		0.1	8		
			B	Db	g cm^{-3}	1.2		0.1	7		
			A	Silt+Clay	%	30.1		3.2	15		
			B	Silt+Clay	%	28.4		4.4	22		
			A	Exch. Ca+Mg	mg 100 g^{-1}	0.6		0.4	83		
			B	Exch. Ca+Mg	mg 100 g^{-1}	0.3		0.1	76		
McFee and Stone (1965)	New York	Spruce	A2	OM	%	2.0			52		
			A2	N	%	0.1			45		
			B2h	OM	%	7.0			26		
			B2h	N	%	0.2			33		
			B2ir	OM	%	4.3			30		
			B2ir	N	%	0.1			33		
Ike and Clutter (1968)	NE Georgia	Red pine plantation	A2	OM	%	3.5			57		
			A2	pH		4.9			7		
			A2	Avail. P	ppm	9.1			46		
			A2	Exch. K	ppm	87.3			47		
			A2	Exch. Ca	ppm	98.1			225		
			A2	Exch. Mg	ppm	35.5			87		
			A2	Sand	%	59.1			9		
			A2	Silt	%	24.7			16		
			A2	Clay	%	16.2			20		
			B2	pH		5.3			4		
			B2	Avail. P	ppm	1.3			57		
			B2	Exch. K	ppm	54.3			54		
			B2	Exch. Ca	ppm	41.6			148		
			B2	Exch. Mg	ppm	36.8			52		
			B2	Sand	%	48.5			17		
			B2	Silt	%	20.7			22		
			B2	Clay	%	30.8			25		

able 1. continued

Author	Location	Cover Type	Soil Type	Variable	Units	Mean	SD	SE	CV%	n	N
Cameron *et al.* (1971)	Alberta		Belloy field 0-15	N	kg ha^{-1}	15.4	7.3		47	208	
			Belloy field 15-30	N	kg ha^{-1}	5.8	5.0		87	208	
			Belloy field 30-61	N	kg ha^{-1}	1.6	2.2		134	208	
			Belloy field 0-15	P	kg ha^{-1}	50.5'	20.3		40	208	
			Belloy field 15-30	P	kg ha^{-1}	16.2	10.1		63	208	
			Belloy field 30-61	P	kg ha^{-1}	4.5	4.1		91	208	
			Belloy field 0-15	K	kg ha^{-1}	360.7	118.2		33	208	
			Belloy field 15-30	K	kg ha^{-1}	342.5	116.1		34	208	
			Belloy field 30-61	K	kg ha^{-1}	404.6	58.3		14	208	
			Belloy field 0-15	pH		5.8	0.5		9	208	
			Belloy field 15-30	pH		5.4	0.4		7	208	
			Belloy field 30-61	pH		6.7	0.8		11	208	
			Chancellor field 0-15	N	kg ha^{-1}	19.6	7.5		38	28	
			Chancellor field 15-30	N	kg ha^{-1}	13.2	5.5		41	28	
			Chancellor field 30-61	N	kg ha^{-1}	11.4	7.3		64	28	
			Chancellor field 0-15	P	kg ha^{-1}	31.7	20.0		63	28	
			Chancellor field 15-30	P	kg ha^{-1}	7.1	5.6		78	28	
			Chancellor field 30-61	P	kg ha^{-1}	1.4	4.8		354	28	
			Chancellor field 0-15	K	kg ha^{-1}	1017.3	154.8		15	28	
			Chancellor field 15-30	K	kg ha^{-1}	787.1	150.7		19	28	
			Chancellor field 30-61	K	kg ha^{-1}	634.2	171.9		27	28	
			Chancellor field 0-15	pH		6.6	0.8		11	28	
			Chancellor field 15-30	pH		7.1	0.6		9	28	
			Chancellor field 30-61	pH		8.0	0.3		4	28	

Holland *et al.* (1967) found that the levels of total variation encountered in samples from 0-15 cm depth were similar to those encountered from 15-30 cm depth. However, calculations based on their data indicate that when the standard error is compared with the mean for each depth, there is a definite increase in relative variation in the 15-30 cm depth samples. Data presented by Metz *et al.* (1966) showed higher values of CV for P as depth increases. A study by Harradine (1949) showed that many soil properties tend to be more variable in younger soils than in older, or more weathered soils. Harradine (1949) found a significant decrease in variance of available P in the surface horizons when compared with that of the less weathered, deeper horizons. Opposite views were presented by Peterson and Calvin (1965), who suggested that the subsoil could be sampled at lower frequency than the topsoil because variation generally decreases with increasing depth. Studies by Ike and Clutter (1968) also showed only a small increase in CV for P and K with depth. Usher (1970) found that small volumes of soil with high nutrient concentration existed in forest soils such that N was extremely variable over short distances while P was relatively homogeneous.

Bracewell *et al.* (1979) studied the variability of OM and exchangeable cations with the A_2 horizon of an iron podzol at Aberdeen, Scotland. Soil samples in this study was separated by distances of 0.5 m, 10 m, 500 m and 8000 m. Analysis of variance with respect to distance between samples showed that all the properties (OM, total C, P and N, exchangeable Ca, Mg, Na, K, pH and available P) examined exhibited considerable variation over short distances (0.5-10 m). Reported CV values for the above study ranged from 7% for pH and 74% for exchangeable Mg. They concluded that all soil properties examined showed marked variation over only a meter distance, whilst base status and humus types were variable over a distance of kilometers. The variability in the above study were probably due to biological activity in the soil (Bracewell *et al.* 1979).

In the temperate and Boreal forest zones, interest in forest floor characterization makes it desirable to determine the variability of soil properties. Forest floor variability have been well examined by (Mader 1963, McFee and Stone 1965, Grier and McColl 1971, Lowe 1972). Arp and Krause (1984) studied forest floor lateral variability on Orthic Ferro-humic podzol soil in central New Brunswick. They observed that CV of parameters varied from 6.6% for total C to 178% for 2 N KCl extractable NO_3-N. They also observed that concentrations (measured in ppm or percent) were in each case less variable than absolute amounts (measured in kg ha^{-1}). They concluded that the forest floor was highly variable in most of its physical and chemical characteristics, making it mandatory to collect a larger number of samples to estimate population means of these properties with a general 95% confidence precision of at least ±10%.

Krumbach and Bassett (1960) examined in detail the variability of soil properties on a 15.5 x 18.3 m plot of Falaya silt loam, which is considered one of the more variable of the loessial-derived soils. To achieve 95% confidence precision of at least ±10% mean values for the plot (at the 21-42 cm depth), they found that 5 observations were required for moisture content, Db and silt content; 10 samples for clay and 30 samples for sand content. For OM content (CV 39%), approximately 60 samples were needed to obtain the above degree of precision.

Ike and Clutter (1968) collected data from 123 forested plots generally in 800 m^2 in size in the Blue Ridge mountains of northeast Georgia to estimate the variability of physical and chemical properties of the soil. They observed that the use of two to four pits per plot in similar soils would seem to be adequate for all the physical properties. Equally precise estimates for OM, available P and exchangeable cations, normally required more than four pits. Although the CV observed in the above study seemed large, the relative differences in variance among pH and exchangeable cations probably resulted from differences in scales of measurements (logarithmic vs. linear). So the 10% standard error of the mean was probably either unreasonably high for estimates of pH or unrealistically precise for exchangeable Ca or Mg. Since majority of the plots they sampled showed evidence of past cultivation, they attributed the high variation among plots to previous management practices.

In a study of variability in soils supporting red pine (*Pinus resinosa* Ait) in Massachusetts, Mader (1963) found that precise estimates of plot means for OM and exchangeable cations in soil-site studies required "prohibitively" large number of pits per plot in comparison to the number of pits needed to determine such properties as Db and texture. Mader further found that the CV for total CEC was much less than the CV for individual exchangeable bases.

Grier and McColl (1971) found that the mean values of properties such as total C, total N and soil pH could be estimated with less than 30 samples for a sampling error of 10%, or less with 95% confidence. They further observed that many of the properties could be adequately estimated with 15 samples or less.

Quesenel and Lavkulich (1980) studied nutrient variability of forest floors near Port Hardy, British Columbia. They reported that 15 samples were adequate to characterize the means at 10% allowable error with a 95% confidence level for total N, C, pH and CEC. Greater than 15 samples were required for exchangeable bases for the same level of accuracy and confidence. They further reported that even at 25% allowable error and 90% confidence, 40 and 16 samples respectively, were required for exchangeable Ca and Mg. Similarly, Mollitor *et al.* (1980) working on flood-plain soil found that while less than 10 samples were needed to characterize Db and pH, over 1000 samples were necessary to estimate K levels within 10% of the mean at 95% confidence.

Keogh and Maples (1967) found that the size of field or sampling area did not affect the CV appreciably. Hemingway (1955) found no general increase in error as the size of area which samples represent was increased. Ball and Williams (1968) emphasized that a large proportion of spatial variability occurs over small distances, even on non-cultivated and freely drained soils which are as nearly uniform as any soils are likely to be. McIntyre (1967) found increased variance for P with distance. Similarly, Cipra *et al.* (1970) found that pits spaced 90 m apart often varied as much fertility in levels as compared to pits spaced 8-145 km apart, while pits 3 m apart were much less variable.

3.0. MATERIALS AND METHODS

3.1.0. STUDY AREA

Ghana is bordered on the east by Togo, on the west by Côte d'Ivore, on the north by Burkina Faso, and on the south by the Atlantic Ocean. Ghana lies approximately between latitudes 4° 45' and 11° 11' N, and 1° 12' E and 3° 15' W, and has an area of 238,537 square kilometres. From the coast the country extends to a distance of about 710 kilometres northward and 538 km from east to west. Much of the country is gently undulating with marked escarpment, but no great elevation differences (Prah 1994).

The high forest zone covers about a third of Ghana's land area (82,000 km^2) and it is part of the Guineo-Congolean phytogeographical region. The flora and fauna have strong affinities with those of Côte d'Ivore, Liberia and Sierra Leone and a lesser affinity with the Nigerian forest from which they are separated by the Dahomey gap . The Southern part of Ghana may be divided into four ecological types each with distinct associations of plant species and corresponding rainfall and soil conditions (Hall and Swaine 1981; Figure 2).

The four broad ecological types are: Wet Evergreen (WE), Moist Evergreen (ME), Moist Semideciduous (MSD) and Dry Semideciduous (DSD). Floristically, these are synonymous with the *Cynomentra-Lophira-Tarrietia*, *Lophira-Triplochiton*, *Celtis-Triplochiton* and *Antiaris-Chlorophora* associations respectively recognised by Taylor 1960. The MSD is further divided into the north-west (MSNW) and south-east (MSSE) subtypes. The remaining 156,537 km^2 (two-thirds of the land area) is mainly covered by Savanna-woodland, Coastal scrub and Grassland, and Maritime (Taylor 1960).

The moist Semideciduous forest is the most extensive forest type in Ghana and is nearly the same as Taylor's (1960) *Celtis-Triplochiton* Association (Hall and Swaine 1981). This forest is made up of a large variety of plant species which are arranged in a series of well-marked layers. A remarkable feature about the moist semideciduous forest is that, while the trees in the lower storey are usually evergreen, taller members of the same species in the higher storeys may be deciduous. Owing to its large extent and differences in climatic conditions, the character of the Semideciduous forest changes gradually from the south to north (Boateng 1966). Trees in this type of forest often attain heights between 50 m and 60 m.

3.1.1. Study Site

The study for this thesis was conducted in the Ashanti Region of the Republic of Ghana. The forest districts are located in the moist semideciduous forest zone and lie between 5° 55' and 7° 10' N latitudes, and 1° 25' and 2° W longitudes. The study sites lie between 150 and 600 m in altitude.

The natural vegetation of this study area falls within the Moist Semideciduous forest zone (Figure 2), and it is characterised by plant species of the *Celtis-Triplochiton* association (Taylor 1960). Some of the tree species found in this zone are *Triplochiton scleroxylon* (K. Schum), *Terminalia ivorensis* (Limbo), *Terminalia superba* (Engl. el Diel), *Celtis milbraidii* (Engl.), *Ceiba pentandra* (Linn.), *Milicia excelsa* (Welm), *Sterculia oblonga* (Mast), and *Pycnanthus angolensis* (Welm).

The Ashanti region falls within the equatorial climatic zone with a rainfall regime which is typical of the moist Semideciduous forest zone. This zone has two well defined rainfall seasons with an annual range of 1500-2000 mm. The major rainy season occurs from mid-March to the end of July with a peak in June. The minor rains commence in September and end in mid-November. From mid-November to mid-March, dry desiccating Harmattan winds blow across the area from the north. The temperatures of this area ranges between 21° C and 32° C with little fluctuations.

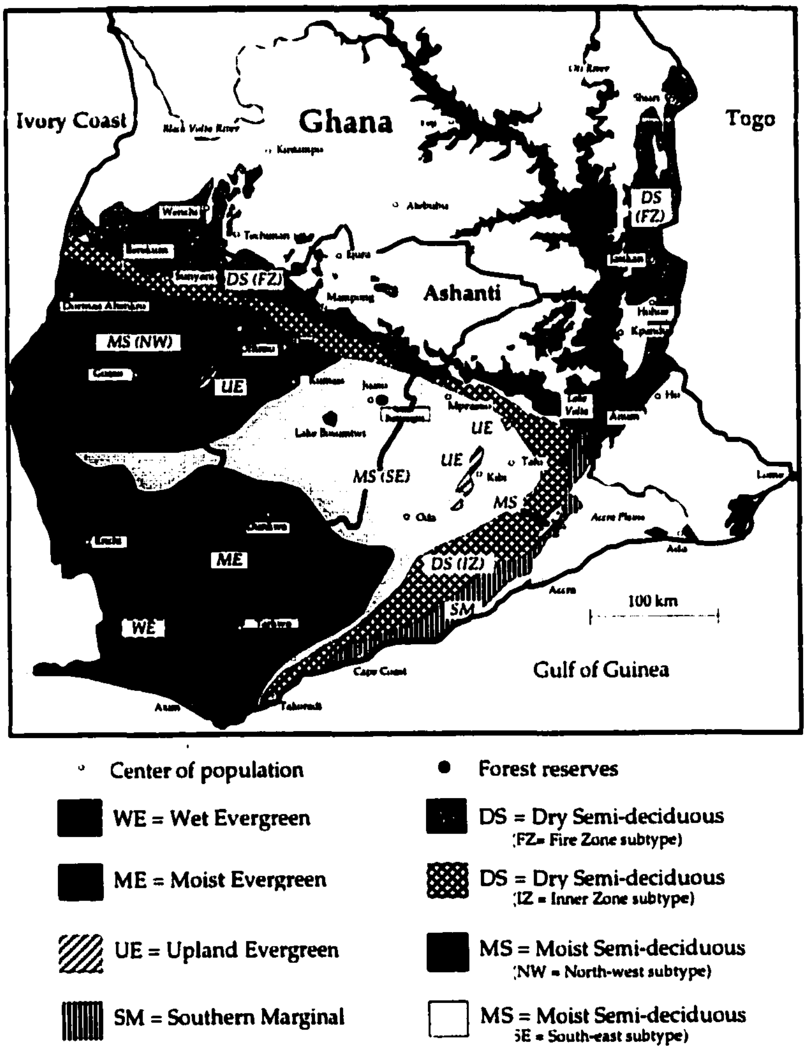


Figure 2. Study region and vegetation groups of southern Ghana (adapted from Hall and Swaine 1981).

Most of the area under the high forest zone is underlain by ancient rocks containing considerable proportions of quartzite, granite, schist and gneisses. The highland rims on the north and east part of Ghana consists of a series of old, dissected peneplains giving rise to a gently undulating topography (Boateng 1966). The forest soils are zonal, and belong to the soil great family group of deep well drained soils called *Latosols* which is subdivided into *Ochrosols* and *Oxysols* (Figure 3). The *Ochrosols* are usually red or reddish brown on summits and upper slopes of hills, orange brown or brown on the middle slopes, and yellow-brown on the lower slopes. They are generally better drained and less acidic than the *Oxysols* and cover a much larger area. In the Ashanti region, the *Oxysols* cover relatively small areas are highly leached, and tend to be more acidic and less rich in humus than *Ochrosols*. The forest Ochrosols are referred to as Haplic Ferralsols (FAO UNESCO 1988).

In areas with rainfall above 2000 mm per annum, both *Ochrosols* and *Oxysols* occur, and such soils are referred to as *Ochrosol-Oxysol* integrates (Boateng 1966; Figure 3). This study was carried out on the forest *Ochrosols* where teak plantations were introduced through the direct planting system by the Forestry Department in the late 1960's. The forest *Ochrosols* are referred to as Haplic Ferralsols (FAO/UNESCO 1998). The forest Ochrosols in the Juaso and Offinso forest reserves belong to Juaso and Ofin soil series respectively (Adu 1992). All teak plantations were established on sites previously occupied by natural forest vegetation. Areas of natural forest were cleared by hand and the slash was burned. Other site disturbance was minimal and teak seedling stumps were planted on site within a year. No agricultural crops were present on the sites during this time. Although some individuals of valuable timber species were left on the cutover, they did not affect the establishment and growth of the teak plantations.

3.2. SURVEY PROCEDURES

In May 1997, using maps of forest reserves and plantation records from the Planning Branch (Forestry Department, Ghana), ground surveys were conducted at three Forest Districts in the Ashanti region. Two Forest Districts and three forest reserves were randomly selected for this study namely: Opro, Afram (Offinso Forest District), and South Fomangsu (Juaso Forest District) forests (Figure 4). Of the 20 compartments of teak plantations in the three forest reserves, three compartment pairs of teak and adjoining natural forests were randomly selected for the study. Since no base line (soil) data of the plantations were available, the adjoining natural forests were chosen and used for comparisons. The teak plantations and adjoining natural forests were separated by boundary lines except compartments 4 and 7 of South Fomangsu forest reserve which were separated by a highway. These compartments of teak plantations and adjoining natural forests were perceived to have similar climatic, physiographic and soil components prior to the conversion of the adjoining natural forests to teak plantations (District Forestry Officer personal comm. 1997). Sites were carefully selected as to avoid areas of variable water table or areas with gleyed soils. However, it is realised that fluctuating water tables may have an important effect on tree mineral nutrition but studies of soil moisture regimes were beyond the scope of this thesis.

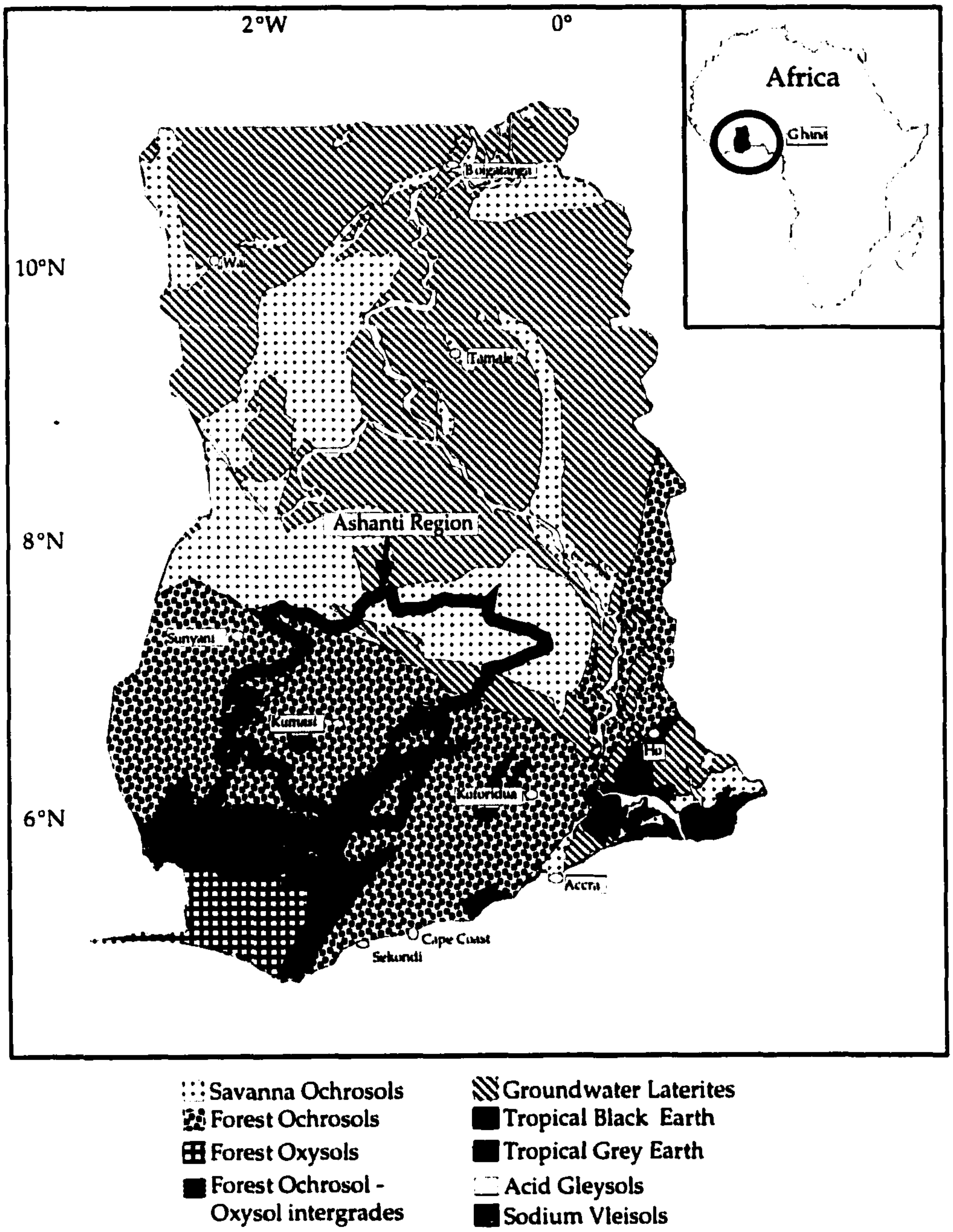


Figure 3. Soil groups of Ghana (adapted from Boateng 1966).

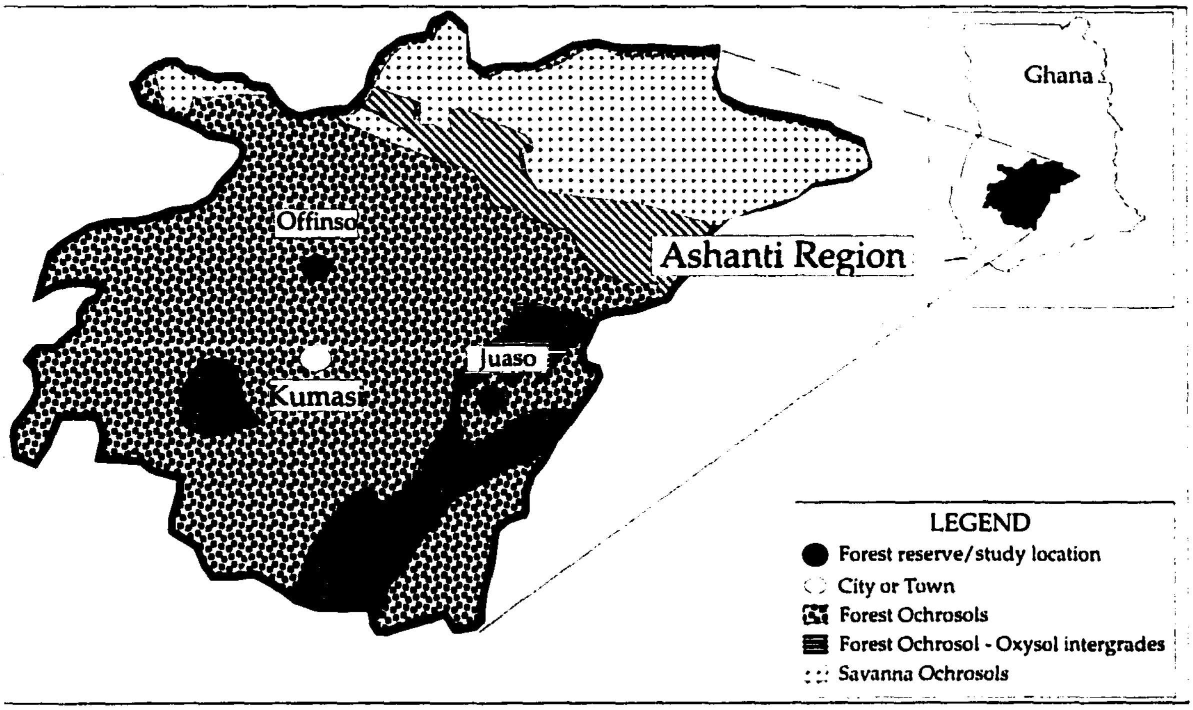
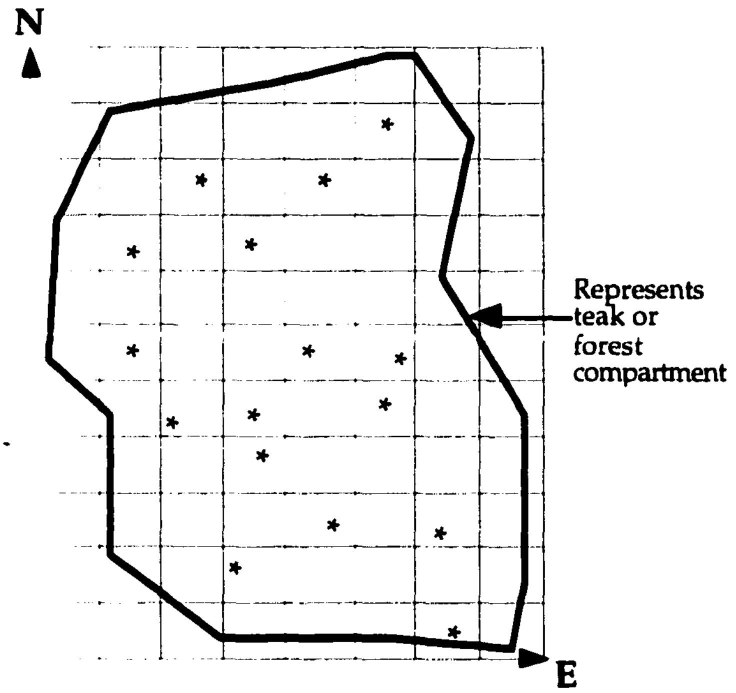


Figure 4. Soil groups of the Ashanti region (adapted from Boateng 1966).

Square grids of 0.5 ha for South Fomangsu forest reserve and 1.0 ha for Opro and Afram forest reserves were drawn on compartment maps and numbered (Figure 5). The grid sizes were chosen based on the size of the compartment (Table 2). With the help of a random number generator, 16 numbers were selected at random to correspond to sixteen grids. Sample points were then located at random within each selected grid.

The teak plantations were established in poorly stocked forest reserves by the Forestry Department from the late sixties to the late seventies through direct plantations and the Taungya system. Compartments selected for this study were established through direct plantations. Details of the study area are given in (Table 2).



Represents 1 ha (Opro River and Afram Headwaters) or 0.5 ha (South Fomangsu)

* Represents one randomly chosen soil pit

Figure 5. Schematic representation of sampling design

Table 2. Forest District, Forest Reserve, Compartment Number[z], Plantation age

Location (District)	Forest Reserve	Cpt.[z] No.	Plantation age (yrs)	Planted area (ha)	natural forest (ha)	Stem/ha.
Offinso	Opro River	17	20	63	47	270
Offinso	Afram Headwaters	4	17	90	66	200
Juaso	South Fomangsu	4	27	16[y]	94[x]	240

[y]Area of coupe 9 of cpt 4, [x]Area of cpt 7

Soil profile descriptions (Appendix XVII) were done for a one cubic metre pit for each of the compartments according to Agric. Can. (1987). Colours were determined using Munsell colour chart (Anon. 1973). Soil samples were collected from depth of 0-20 cm and 20-40 cm depth for all compartments. Bulk density samples were collected from both depths for all the sixteen soil pits in each compartment using a sharpened core sampler technique (Rowell 1994). A 50 cm^3 cylinder was pressed into the soil with the aid of a sleeve and gently tapped with a rubber mallet. Particular care was exercised to drive the cylinder in a straight line. Sample with a surplus of soil was trimmed with the aid of a trowel and placed in plastic bags. Separate soil samples for chemical and texture analyses were put into plastic bags and taken to the School of Forestry (Sunyani, Ghana) soil science laboratory for preparation. Prepared soil samples were then taken to the Savanna Agricultural Research Institute's soil chemistry laboratory (Nyankpala, Ghana) for analyses. Bulk density samples were taken to the laboratory, weighed, and were dried to a constant weight in an oven at 110° C. Details of sampling intensity for bulk density and macronutrients are given (Table 3).

Table 3. Sampling intensity for soil macronutrient and bulk density.

Cover type	No. of cpt[z]	No. of pits/ cpt	No. of samples/pit	Bulk density	Macro-nutrient	Total
Teak	3	16	2	96	96	192
Natural forest	3	16	2	96	96	192
Total	6	32	4	192	192	384

[z] Compartment

3.3. ANALYTICAL METHODS

Particle size distribution (% sand, silt and clay) was determined by the pipette method (IITA 1979). Bulk density was determined on core samples according to Rowell (1994). Soil pH was determined potentiometrically, both in distilled water and in 0.01M $CaCl_2$ solution using a soil to solution ratio of 1:2.5 (IITA 1979). Available P was estimated using a soil to extraction solution ratio of 1:7 and the Bray I method. Measurements for P were made at 885 nm wavelength on a Philips Pyre Unicam uv/visible spectrophotometer. Total nitrogen (total-N) was estimated by the Kjeldahl method (IITA 1979). Organic matter content was determined through loss on ignition at 600°C in a muffle furnace (Ball 1964). Exchangeable Ca, Mg, Na and K were extracted by 1N ammonium acetate solution and determined by Inductively Coupled Plasma Elemental Analyzer (ICP) using the methods described by Simard (1993) and modified slightly according to Meyer and Vanson (1997). Soil pH, Db, available P, total-N and texture were determined at Savanna Agricultural Research Institute's soil chemistry laboratory at the Nyankpala in Tamale, Ghana. The remaining analyses were done at the Forest Soils and Instrumentation Laboratories at Lakehead University, Thunder Bay, Ontario.

Computation of Nutrient Contents

Total nutrient contents were estimated for teak plantations and natural forests by:

$$\text{Total nutrient content (kg ha}^{-1}\text{)} = [\text{Nc (eq kg}^{-1}\text{) x weight of soil (kg ha}^{-1}\text{)] x equivalent weight (kg eq}^{-1}\text{)} \quad [1]$$

$$\text{Nc (eq kg}^{-1}\text{)} = \text{Nc (eq / 100) x 10} \quad [2]$$

$$\text{Nc (eq / 100 g)} = \text{Nc meq / 100 x eq / 1000 meq} \quad [3]$$

$$\text{Weight of soil (kg ha}^{-1}\text{)} = [\text{h - (h x CF / 100)] x Db x kg / 1000g x [A x 10}^{8}\text{] ha}^{-1} \quad [4]$$

where:

Nc = nutrient concentration

h = thickness of soil horizon (cm)

CF = Coarse fragment (%)

Db = bulk density (g cm^{-3})

A = area (cm^2) = 1 ha.

3.4. STATISTICAL ANALYSES

The statistical procedures included one-way analysis of variance (ANOVA), an F-test for equality of variance and paired *t*-test comparison. The F-test for equality of variance (Snedecor and Cochran 1967) was used to test whether the soil data could be combined for the three sites. For each sample, concentrations of exchangeable Ca, Mg, K, Na, available P, %N and absolute amounts for total N, P, K, Ca, Mg, Na were calculated. Distribution problems in some of the variables were corrected by transformation where necessary. The statistical treatment of the 384 samples associated with the various physical and chemical properties given in Tables 4 and 5 included calculations of mean ($\overline{X}$), standard deviation (SD), and the coefficient of variation (CV). The maximum and minimum values for each property were also noted in order to demonstrate the range in values found for each property and for each vegetation type. The data were further analyzed to determine the number of samples necessary to obtain the mean value of a property within a specified allowable error and confidence level. The general procedure involved using the calculated CV's of the properties and then, by iterative methods, obtaining the number of samples required for allowable error of 10 percent at 95 percent confidence level. The calculations were performed using equation 5 (Husch *et al.* 1982).

$$n = \frac{t^2_{\alpha/2,\,df} * CV^2}{AE\%^2} \qquad [5]$$

where n is the number of sample units needed to estimate the mean with a specific allowable error and probability, $t_{\alpha/2,\,df}$ is the value of student's *t* distribution with n-1 degrees of freedom, CV is the coefficient of variation and AE is the allowable sampling error in percent.

The data were analyzed for allowable errors of 10, 15 and 20 percent at 95 percent confidence level. An allowable error of 10 percent at 95 percent confidence is normally considered acceptable (Blyth and Macleod 1978). It was decided to determine the number of samples required for the same confidence level and greater allowable error since it may not always be practical or economical to collect the number of samples necessary to obtain an estimate of the mean with allowable error of 10 percent at 95 percent confidence level.

4.0. RESULTS

Summary statistics for soil physical and chemical properties by individual compartments in Afram Headwaters, Opro River and South Formangsu forest reserves are given in Appendices (I-XIII).

Preliminary analyses involved correction of distribution problems and test for equality of variance between the three compartments of teak plantations and adjoining natural forests, respectively. The null hypotheses for equality of variances was accepted for all the three paired tests. Data analyses were therefore based on combined data from the three forest sites. A comparison of teak and natural forest means and standard errors of the means for nutrient concentrations is given in Figure 6. Figure 8 shows the comparison of nutrient contents in topsoil and subsoil separately as well as and topsoil and subsoil combined for soils under teak and natural forests. Percent OM, pH and physical properties of the topsoil and subsoil are given in Figure 7. Standard deviations, coefficients of variations and estimates of sample sizes for texture, OM, pH, total N, available P, and exchangeable K, Ca, Mg and Na are given in Tables 4 and 5.

4.1. GENERAL VARIABILITY OF SOIL PROPERTIES UNDER TEAK PLANTATIONS

In the 0-20 cm depth (topsoil) CV's for chemical properties ranged from 8 percent for pH to 72 percent for available P (Table 4). Similarly, physical properties showed high CV's ranging from 14 percent for Db to 36 percent for percent clay content.

In the topsoil, four samples would be required to estimate means of pH. However, due to the higher CV's observed for the chemical properties in the 0-20 cm depth, 4-207 samples would required if the same precision is desired (Table 4). Furthermore, 11-52 samples would be required if the same precision level is desired to estimate means of Db, sand, silt and clay in the topsoil.

In the 20-40 cm depth, CV's for chemical properties ranged from 16 percent to 116 percent, and are reflected by high values of n (Table 4). For the physical properties, CV's were comparable to that of the 0-20 cm depth which is an indication that physical properties varied less with depth than chemical properties (Table 4). Unlike the 0-20 cm depth, CV for pH was slightly higher in the 20-40 cm depth. In general 13-45 samples would be adequate or required to estimate pH, K, Ca, Na, and total N. Due to the higher variations observed for P and Mg in the 20-40 cm depth, 229-517 samples would be required to estimate their means (Table 4). Also 12-40 samples would be adequate to estimate the means of OM, Db, sand, silt and clay in the 20-40 cm depth under teak plantations.

Table 4. **Physical and chemical properties of soils under teak plantations (Afram, Opro and South Formangsu)**

Property	Transformation	Summary statistics[z]		CV%	No. of samples[y]		
		Mean	(SE)		n_1	n_2	n_3
		TOPSOIL (0-20 CM)					
N (%)	N^{-1}	5.30	0.23	31	37	19	12
P (mg kg^{-1})	$\sqrt{P}$	0.89	0.09	72	207	91	52
Exch. K (cmol(+)kg^{-1})	Log K	0.62	0.03	36	51	24	15
Exch. Ca (cmol(+)kg^{-1})	$\sqrt{Ca}$	3.42	0.12	25	27	14	9
Exch. Mg (cmol(+)kg^{-1})	Log Mg	0.45	0.03	47	88	39	24
Exch. Na (cmol(+)kg^{-1})	$\sqrt{Na}$	0.13	0.01	32	42	20	13
pH	none	6.69	0.08	8	4	2	1
OM (%)	"	11.18	0.34	21	20	10	6
Db (g cm^{-3})	"	1.30	0.03	14	11	6	3
Sand (%)	"	48.05	1.73	25	27	14	9
Silt (%)	"	35.00	1.20	24	25	13	8
Clay (%)	"	16.95	0.89	36	52	25	15
		SUBSOIL (20-40 CM)					
N (%)	N^{-1}	12.0	0.49	32	34	17	11
P (mg kg^{-1})	$\sqrt{P}$	0.25	0.04	116	517	230	130
Exch. K (cmol(+)kg^{-1})	Log K	0.97	0.03	22	21	11	8
Exch. Ca (cmol(+)kg^{-1})	$\sqrt{Ca}$	2.42	0.11	32	41	20	12
Exch. Mg (cmol(+)kg^{-1})	none	2.90	0.32	76	229	102	58
Exch. Na (cmol(+)kg^{-1})	$\sqrt{Na}$	0.15	0.01	33	45	22	13
pH	none	5.68	0.13	16	13	7	5
OM (%)	"	9.51	0.31	23	23	12	8
Db (g cm^{-3})	"	1.55	0.04	16	12	7	5
Sand (%)	"	35.56	1.60	31	40	19	12
Silt (%)	"	33.55	0.93	19	17	9	6
Clay (%)	"	30.97	1.35	30	38	18	11

[z] Summary statistics in re-expressed units where transformation apply.

[y] Estimate of the number of samples to achieve: n_1 ($\bar{X}$) ± 10% with 95%, n_2 ($\bar{X}$) ± 15% with 95% confidence and n_3 ± ($\bar{X}$) 20% with 95% confidence.

4.2. GENERAL VARIABILITY OF SOIL PROPERTIES UNDER NATURAL FORESTS

In the 0-20 cm depth, CV's for chemical properties ranged from 11 percent for pH to 40 percent for K. In general 9-63 samples would be required (Table 5). For the physical properties, CV's ranged from 21 percent for Db to 39 percent for percent clay. The estimated number of samples required increased from 20 samples for Db the least variable to 60 samples for percent clay, the most variable physical property in this case (Table 5).

In the 20-40 cm depth, CV's for chemical properties ranged 16 percent for pH to 86 percent for available P indicating that more samples (12-296) would be required to estimate means (Table 5). In general, the results showed an increase in CV's for the chemical properties with depth. These trends makes it mandatory to collect more samples for the chemical properties in the 20-40 cm depth as indicated in Table 5. Variation for percent sand, silt and clay were high, but lower for Db (Table 5). Coefficients of variations for sand, silt and clay increased with depth except for Db which had CV of 10% in the 20-40 cm depth as compared to CV of 21% in the 0-20 cm depth.

Table 5. Physical and chemical properties of soils under natural forests (Afram, Opro and South Formangsu forest reserves)

	Transformation	Summary statistics[z]			No. of samples[y]		
Property		Mean	(SE)	CV%	n_1	n_2	n_3
		TOPSOIL (0-20 CM)					
N (%)	N^{-1}	3.47	0.14	29	34	17	11
P (mg kg^{-1})	$\sqrt{P}$	1.60	0.04	28	32	17	11
Exch. K (cmol(+)kg^{-1})	Log K	0.45	0.03	40	63	29	18
Exch. Ca (cmol(+)kg^{-1})	$\sqrt{Ca}$	4.03	0.13	22	22	11	8
Exch. Mg (cmol(+)kg^{-1})	Log Mg	0.55	0.02	26	28	14	9
Exch. Na (cmol(+)kg^{-1})	$\sqrt{Na}$	0.12	0.00	26	29	14	10
pH	none	6.95	0.11	11	9	3	2
OM (%)	"	12.53	0.46	26	28	14	9
Db (g cm^{-3})	"	1.17	0.04	21	20	11	7
Sand (%)	"	53.90	1.90	25	26	13	9
Silt (%)	"	33.22	1.25	26	29	14	10
Clay (%)	"	13.09	0.74	39	60	29	18
		SUBSOIL (20-40 CM)					
N (%)	N^{-1}	14.0	0.90	45	80	37	22
P (mg kg^{-1})	$\sqrt{P}$	0.64	0.08	86	296	129	74
Exch. K (cmol(+)kg^{-1})	Log K	0.98	0.04	30	36	18	11
Exch. Ca (cmol(+)kg^{-1})	$\sqrt{Ca}$	2.10	0.11	35	50	24	15
Exch. Mg (cmol(+)kg^{-1})	none	2.44	0.26	74	213	95	54
Exch. Na (cmol(+)kg^{-1})	$\sqrt{Na}$	0.113	0.01	53	111	52	30
pH	none	5.51	0.12	16	12	7	5
OM (%)	"	8.19	0.49	42	68	30	19
Db (g cm^{-3})	"	1.57	0.02	10	7	2	2
Sand (%)	"	44.08	2.00	31	39	20	12
Silt (%)	"	30.54	1.14	26	29	14	9
Clay (%)	"	25.39	1.47	40	63	30	18

[z] Summary statistics in re-expressed units where transformation apply.

[y] Estimate of the number of samples to achieve: n_1 ($\bar{X}$) ± 10% with 95%, n_2 ($\bar{X}$) ± 15% with 95% confidence and n_3 ± ($\bar{X}$) 20% with 95% confidence.

4.3. COMPARISON OF SOIL MEANS UNDER TEAK PLANTATIONS AND NATURAL FORESTS

A comparison of teak and natural forest means and standard errors of the means for chemical and physical properties of topsoil and subsoil is given in Figures 6 and 7.

Total N, available P, exchangeable K, Ca, Mg and OM in the topsoil were significantly higher ($P <0.0004$, $P <0.0009$, $P <0.00013$, $P <0.0015$ and $P <0.0043$ respectively) under the natural-forests than under the teak plantations (Figure 6). Percent N varied from 0.098 to 1.18 with mean and confidence interval (0.22±0.04) under the teak plantations, and from 0.17 to 0.79 (0.31±0.02) under the natural forests (Appendix XIV and XV). Phosphorus varied from 0.00 to 9.62 mg kg^{-1} (1.19±0.46) under the teak plantations, and from 0.00 to 28.42 mg kg^{-1} (4.16±1.68) under the natural forests (Appendix XIV and XV), respectively. Exchangeable K varied from 0.103 to 0.76 cmol(+)kg^{-1} (0.28±0.04) under the teak plantations, and varied from 0.136 to 0.85 cmol(+)kg^{-1} (0.38±0.04) under natural forests (Appendix XIV and XV). Similarly, exchangeable Ca varied from 4.35 to 29.60 cmol(+)kg^{-1} (12.38± 1.86), and from 5.0 to 34.45 cmol(+)kg^{-1} (16.99±2.12) under teak and natural forests (Appendix XIV and XV), respectively. Exchangeable Mg and OM varied from 1.53 to 6.30 cmol(+)kg^{-1} (3.17±0.48) and 5.70 to 17.20 (12.53±0.92), and 5.30 to 17.0 cmol(+)kg^{-1} (11.18±0.68) under the natural forests and teak plantations (Appendix XIV and XV), respectively. Sodium also varied from 0.003 to 0.002 cmol(+)kg^{-1} (0.02±0.0002) under the teak plantations and from 0.005 to 0.033 cmol(+)kg^{-1} (0.01±0.0002) under the natural forests (Appendix XIV and XV).

Analysis of variance showed percent sand was significantly higher ($P <0.0043$) under the natural forests (Figure 7). Percent clay and Db were also significantly higher ($P <0.0012$, and $P <0.018$ respectively) under the teak plantations in the topsoil (Figure 7). Percent sand varied from 25.17 to 71.70 with mean and confidence interval (48.05±3.46) under the teak plantations (Appendix XIV), and from 29.91 to 52.17 (53.90±3.8) under natural forests (Appendix XV). Percent clay varied from 5.58 to 33.89 with mean and confidence interval (16.95±1.78) under the teak plantations (Appendix XIV), and from 7.32 to 41.36 (21.14±2.4) under the natural forests (Appendix XV). Bulk densities varied from 0.69 to 1.76 g cm^{-3} (1.17±0.08) under the natural forests and from 0.51 to 1.67 g cm^{-3} (1.30±0.06) under teak plantations.

In the subsoil, P was significantly higher ($P < 0.0002$) under the natural forests while Na was significantly higher ($P < 0.0027$) under the teak plantations. In the subsoil, P varied from 0.00 to 1.67 mg kg^{-1} (0.15±0.08) under the teak plantations, and from 0.00 to 4.54 mg kg^{-1} (0.71±0.28) under the natural forests (Appendix XIV and XV). Also Na varied from 0.0003 to 0.074 cmol(+)kg^{-1} (0.02 ±0.0002) and from 0.00003 to 0.054 cmol(+)kg^{-1} (0.02±0.00002) under the teak plantations and under the natural forests (Appendix XIV and XV) respectively.

Similarly, Db varied from 0.58 to 1.92 g cm^{-3} (1.55±0.08), and 1.14 to 2.06 g cm^{-3} (1.57±0.04) under the teak plantations and natural forests (Appendix XIV and XV), respectively.

Percent silt and clay were significantly higher ($P < 0.0431$ and $P < 0.0061$ respectively) under the teak plantations whilst percent sand and Db were significantly higher ($P < 0.0013$ and $P < 0.0249$ respectively) under the natural forests (Figure 8). Observed differences for all other measured properties in the subsoil were not statistically significant under both cover types (Figure 6 and 7).

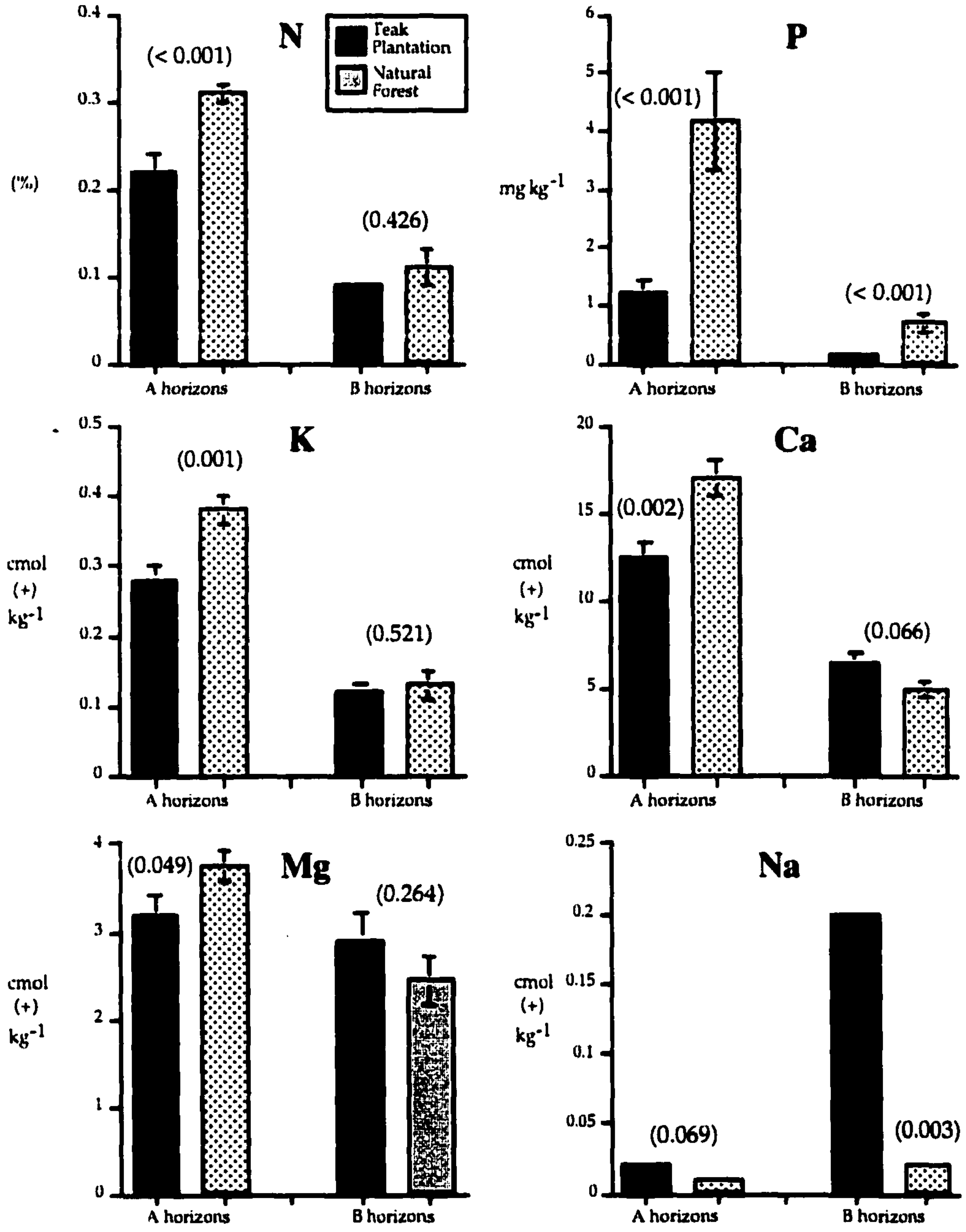


Figure 6 Mean N, P, K, Ca, Mg, and Na concentrations in topsoil and subsoil (denoted by 'A horizons' and 'B horizons', respectively) under teak and adjacent natural forests. Numbers in parentheses represent probabilities; bars represent standard errors of means; all n = 48.

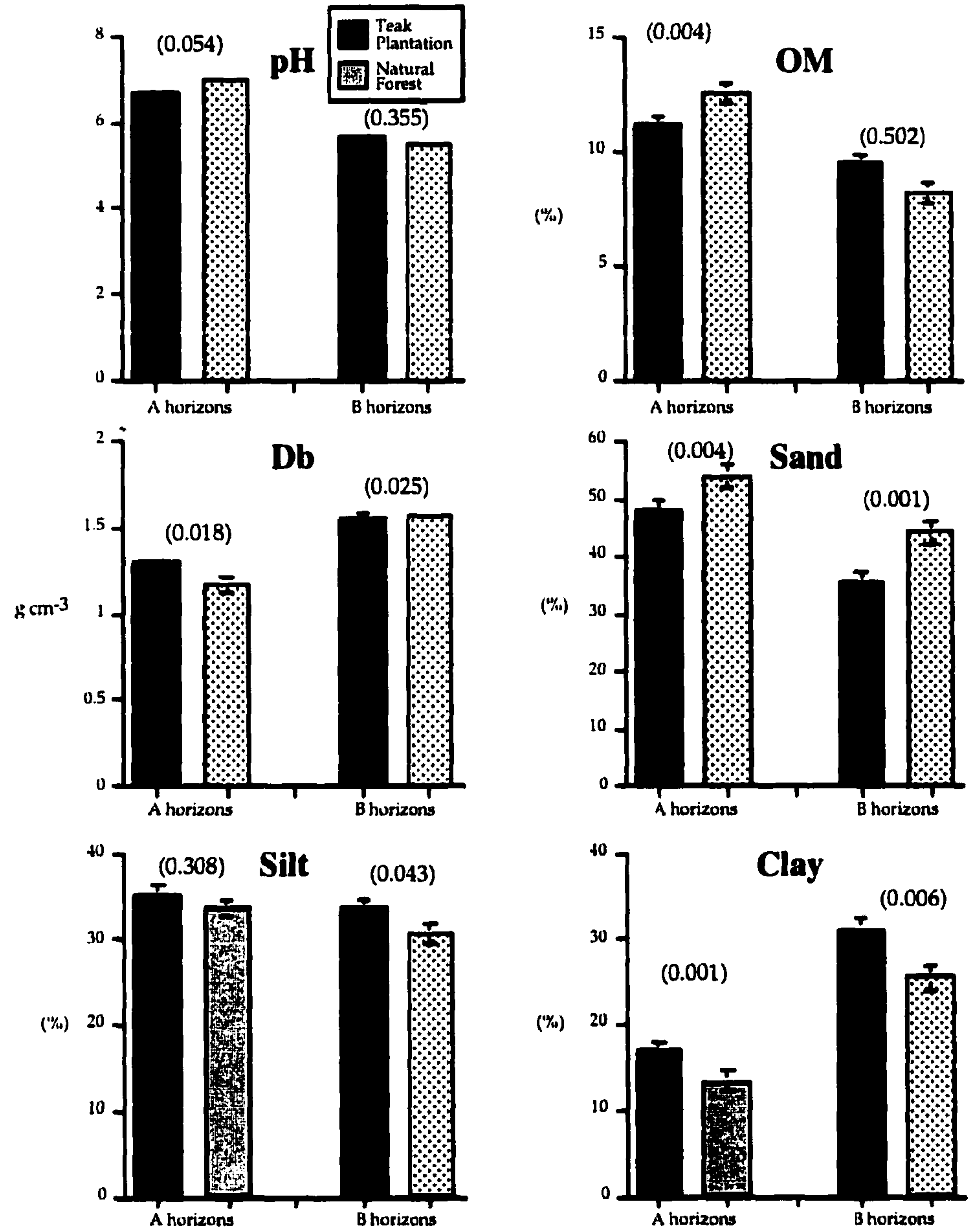


Figure 7. Mean pH, OM, Db, Sand, Silt,, and Clay distributions in topsoil and subsoil (denoted by 'A horizons' and 'B horizons', respectively) under teak and adjacent natural forests. Numbers in parentheses represent probabilities; bars represent standard error of means; all n = 48.

4.4. COMPARISON OF MACRO-NUTRIENT CONTENTS OF SOILS UNDER TEAK PLANTATIONS AND ADJOINING NATURAL FORESTS (TOP AND SUBSOIL HORIZON)

In the topsoil, total N, available P, exchangeable K, Ca and Mg were significantly higher ($P < 0.0006$, $P < 0.0081$, $P < 0.005$ and $P < 0.0132$ respectively) under the natural forests as compared to teak plantations. In contrast, exchangeable Na was significantly higher ($P < 0.0436$) under the teak plantations (Figure 8). Nitrogen ranged from 3,551 to 12,431 kg ha^{-1} with mean and confidence interval of 7,112±588 under the natural forests, and from 1,301 to 23,291 kg ha^{-1} (5,183±922) under the teak plantations (Appendix XVI). Phosphorus varied from 0 to 80.67 kg ha^{-1} (11±4) and from 0 to 26.41 kg ha^{-1} (3±1) under the natural forests and teak plantations respectively. Similarly, K, Ca and Mg ranged from 132 to 788 kg ha^{-1} (346±44), 2,213 to 17,238 kg ha^{-1} (7,651±897) and from 359 to 2,042 kg ha^{-1} (1049±99), and 57 to 718 kg ha^{-1} (261±45), 1,832 to 14,715 kg ha^{-1} (5,789±933) and from 357 to 2165 kg ha^{-1} (865±107) under natural forests and teak plantations, respectively. Sodium ranged from 1.79 to 44.83 kg ha^{-1} (13±3) under teak and from 4 to 26 kg ha^{-1} (10±1) under the natural forests.

In the subsoil, observed difference for available P contents was statistically higher ($P < 0.0002$) under the natural forests as compared to teak plantation. Phosphorus ranged from 0 to 5 kg ha^{-1} (1±0) under the teak and from 0 to 15 kg ha^{-1} (2±1) under the natural forests. However, Na was significantly higher ($P < 0.005$) under teak varying from 0 to 77 kg ha^{-1} (23±4) and from 0 to 57 kg ha^{-1} (15±4) under the teak plantations and adjoining natural forests, respectively (Figure 8). Observed differences in Ca, Mg, N and K were not statistically significant under both cover types (Figure 8). Nitrogen varied from 1,197 to 5,769 kg ha^{-1} (2,717±214) and 1,123 to 22,732 kg ha^{-1} (3,191±1076) under the teak and natural forests, respectively. Also K ranged from 52 to 442 kg ha^{-1} (143±23) and from 18 to 687 kg ha^{-1} (158 ±34) under teak and natural forests, respectively. Lastly, Ca and Mg varied from 694 to 17,941 kg ha^{-1} (3,867±773) and from 240 to 3517 kg ha^{-1} (1,029±208) under teak, and from 32 to 8427 kg ha^{-1} (3,096±572) and 193.81 to 2,694 kg ha^{-1} (927±195) under the natural forests.

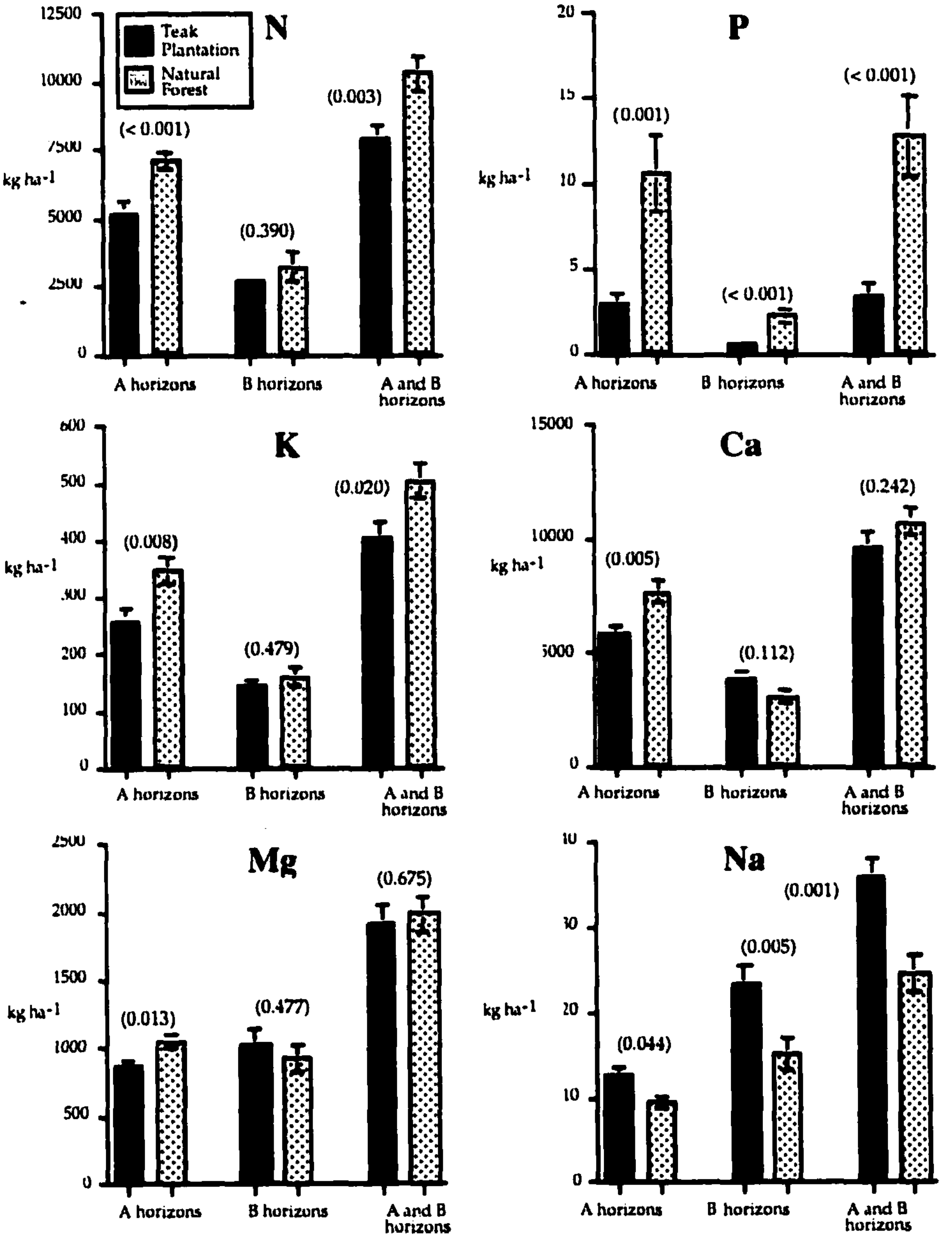


Figure 8. Comparison of means of soil macro-nutrient contents of the topsoil, subsoil, (denoted by 'A horizons' and 'B horizons', respectively) and both combined and subsoil under teak plantations and adjoining natural forests. Numbers in parentheses represent probabilities; bars represents standard error of means; all n = 48.

4.5. COMPARISON OF MACRO-NUTRIENT CONTENTS OF SOILS UNDER TEAK PLANTATIONS AND ADJOINING NATURAL FORESTS (A+B HORIZONS)

Macro-nutrient contents for N, P and K observed in the (A+B) horizons were significantly higher ($P < 0.0029$, $P < 0.003$ and $P < 0.0205$ respectively) under the natural forests. Total N content varied from 4,193 to 26,025 kg ha^{-1} (7,900±946), and from 4,941 to 30,419 kg ha^{-1} (10,303±1,255) under teak and natural forests. Phosphorus also varied from 0 to 29 kg ha^{-1} (3±1) under teak, and from 0 to 84 (kg ha^{-1}) (13±5) under natural forest. Similarly, K ranged from 156 to 934 kg ha^{-1} (404±57) under teak, and from 213 to 1,352 kg ha^{-1} (504±63) under natural forests. Sodium content was higher ($P < 0.0011$) under teak plantations (Figure 8), and varying from 10 to 88 kg ha^{-1} (36±5), and from 6 to 66 kg ha^{-1} (25±4) under natural forests.

5.0. DISCUSSION

5.1. SOIL CHEMICAL PROPERTIES

According to Ahn (1962), soil nutrients in Ghana are largely stored in the topsoil and standing biomass of trees, and maintained by the biogeochemical cycle. Higher nutrient in the surface horizon in the present study may be due to the higher OM content in the surface soils, and is consistent with reports by Ahn (1962), and Salifu and Meyer (1998). The low available P values under both cover types are not unexpected because under tropical conditions most of the P is tied up in the vegetation or by iron and aluminum hydroxides in the subsoil (Nye and Greenland 1965). Despite the low available P values, the natural forests showed a significantly higher P than the teak plantations. The higher nutrient contents observed under natural forests is probably associated with more ground and shrub layer vegetation, litter and the resultant higher OM content (Balagopalan 1995). Differences in OM observed under both cover types can also be attributed to the differences in vegetation type, species composition and age of the forests stands. Soil N and P contents have been shown frequently to be positively related to soil OM (Brady and Weil 1996). Stand undergrowth was sparse and in some parts of the teak plantations undergrowth was absent.

In the present study, it was observed that the topsoil in the natural forests had more favorable structure compared to soils under teak plantations. The low soil nutrient levels (concentrations and contents) found under teak plantations in this study may also be due to the higher demand and nutrient immobilization in teak (Aborisade and Aweto 1990, Chava *et al.* 1989, Nwoboshi 1984). The high rainfall conditions in the Ashanti region may have contributed to the leaching of freshly mineralized basic cations resulting in the deceased values of total and available nutrient pools under the teak plantations.

Soil Na concentration was significantly higher under teak plantations in both the topsoil and subsoil than in the soils under natural forests. Sodium is perhaps the most mobile cation in soils (Wiklander 1980) and the increased leaching of Na may be linked to increased water infiltration in the soil under teak (Prasad *et al.* 1985). Similar findings of increased Na leaching under teak have been reported by (Choubey *et al.* 1987, George and Varghese 1992, Prasad *et al.* 1985, Totey *et al.* 1986).

Soil pH was nearly neutral and did not significantly differ between soils under teak and natural forests. It is possible that the excess Na in soils under teak helped keep the pH high despite the decrease of the other cations under the teak cover. Therefore, pH measures alone are not sufficient to assess the soil nutrient status. Furthermore, Ingestad (1987) postulated that plant nutrient levels are also affected by the proportions of nutrients available in the soil. For the present study, the ratio of exchangeable cation concentrations of Ca:Mg:K:Na in the 0-20 cm depth under teak was 1 : 3.9: 44.2 : 619 and 1 : 4.5 : 44.7 : 1,699 under the natural forest which seems to support the possibility that Ca and K levels were lowered proportionally more than Na (and to a lesser degree Mg) under the teak. Nutrition studies of several coniferous and broadleaf seedling species have revealed optimum cation and anion ratios for tree vigour and growth (Ingestad 1979a, b; Jia and Ingestad 1984). Unfortunately, these types of studies remain to be done for mature tropical species.

Biogeochemical cycling occurs with a defined ecosystem among vegetation, litterfall, and soil through the process of microbial and faunal decomposition. Abiotic conditions (temperature, moisture, *etc.*) favoring chemical decomposition of litter raises the available nutrient status of soils and the efficiency of nutrient cycling. In natural stands, nutrients usually are cycled efficiently between the forest floor and the vegetation and may maintain an overall higher nutrient pool than that of continually burned or harvested sites (Kimmins 1997). The structural and functional adaptations of the natural forests to the climatic and edaphic environment are relatively efficient to maintain and conserve a viable, perpetual ecosystem when compared to plantations (Balagopalan 1995). In addition to the importance of the biogeochemical cycle, the geochemical cycle adds nutrients (inputs) to a site through rainfall, dust, mineral weathering *etc.*; losses of nutrients (outputs) from a site occur as leachates, surface runoff, fire, *etc.* (Kimmins 1997). But replacement of natural forests by teak plantations may create disturbances in the nutrient cycle unbalancing the uptake and release of ions in the ecosystem (Mongia and Bandyopadhyay 1994). Furthermore, observed changes in soil properties attributed to teak plantations may also include changes that occurred during the conversion of the natural forest to teak. It is therefore necessary to take measures to protect the natural forests from being used for high value plantation crops for getting short term benefits as it will reduce the total and available nutrient pool as reported in this study.

5.2. SOIL PHYSICAL PROPERTIES

In the present study, significantly higher clay was noticed through 0-20 cm and 20-40 cm layers in soils under teak plantations compared to soils under natural forests. It was observed that the translocation of clay with depth was higher in teak plantations compared to natural forests. Salifu and Meyer (1998) observed a similar trend which was confirmed by clay mineralogy analysis in a similar ecological forest zone in Ghana. It is possible that the change of the natural forest cover to teak allowed more weathering to occur throughout the soil profile during the transition stage of the cover change. Soils exposure of the one to two year time period before plantation establishment may be subject to more rain infiltration thereby causing more downward movement of clay. Such a hypothesis for the translocation of clay down the soil profile by water was examined by Prasad *et al.* (1985) who attributed higher percentages of clay in the B horizon under teak to previous deforestation and aforestation activities on the sites (Prasad *et al.* 1985).

Substantial changes in Db were observed after natural forests were replaced with teak plantations, suggesting that soil compaction occurred under teak plantations. Salifu and Meyer (1998) similarly reported differences in Db of some soils in the Brong Ahafo region, Ghana. Increased compaction has been shown to affect soil structure and porosity negatively and, hence, can result in a reduction in aeration (Rab 1996, Wert and Thomas 1981). For these reasons, compaction may deteriorate the soil's productivity or make the establishment of the next rotation difficult (Rab 1996, Wert and Thomas 1981). Changes in Db as a consequence of timber harvesting, machinery trafficking and top soil removal have been reported elsewhere (Incerti *et al.* 1987, Johnson *et al.* 1991, Miller and Sirois 1986). Higher Dbs observed under teak plantations may be due to past management practices such as the original plantation establishment and subsequent thinning operations. Bulk densities were found to increase with depth under both cover types. Similar results have been reported by Bell (1973), Karunakaran (1984), Kushalappa (1987), and Salifu and Meyer (1998). The decrease in OM content with depth observed in this study seems to be related to increased Db with depth. The observed changes in physical conditions in this study could probably be due to the conversion of natural forests to teak plantations (Jose and Koshy 1972). Less understorey vegetation and litter under teak also was observed to lead to higher soil erosion potential.

5.3. SPATIAL VARIATIONS AND SAMPLE SIZE ESTIMATION

The extent of forest soil variability encountered in this study was by no means unique. A number of temperate and boreal forests soil research has shown that spatial variation of soil properties are surprisingly large (Beckett and Webster 1971, Usher 1970, Mollitor *et al.* 1980) and makes accurate assessment of forest soil properties often difficult (Mroz and Reed 1991) and also presents major problems in conducting field experiments (Table 1). Furthermore, temperate zone and Boreal forests floor variability have also been examined (Arp and Krause 1984, Grier and McColl 1971, Lowe 1972, McFee and Stone 1965). In all the studies, the authors concluded that forest soils in general and forests floors in particular are highly variable in most of their physical and chemical characteristics, making it mandatory to collect more samples to estimate means of these properties. Though interpretation of data in terms of soils in other areas or under different forested conditions is of doubtful value for Ghanaian soils, such work has served as a valuable frame of reference. McFee and Stone (1965) attributed large variations of soil properties to wind distribution of leaf and twig debris over and around pits, mounds, stumps, and fallen trees. These same factors, plus those associated with tree blow down and soil faunal activity could also lead one to expect large variations for chemical and physical properties of forest soils. It has also been suggested that past management practices such as thinning, cutting as well as wild fires might probably have some influence in the high natural variability under forest stands. The high CV's observed in this study could be due to some of the above mentioned factors, but thinning operations under the teak plantations and harvesting under the natural forests could have greater influence on the CV values.

In general, large values of coefficients of variation (and therefore also for n) may be expected for total N, available P, exchange Ca, K, Mg and Na, but CV's for texture, OM, Db and pH tend to be relatively small. Assuming the means to be true, then low concentrations should always exhibit large coefficients of variation (and large values of n) (Hemingway 1955, Mader 1963). Cameron *et al.* (1971) and Metz *et al.* (1966) observed greater CV values for N and P which decreased with depth. Cameron *et al.* (1971) cautioned that care must be taken in the interpretation of the complementary effect of both nutrient elements as both decrease substantially with depth and could account for the higher CV's at lower depths. The results of this study (Table 4) show that the mean concentrations of N and P decreased with depth whereas the CV's for N and P increased with depth under teak plantations. The high CV observed for P in the Subsoil under the teak could be attributed to the zero values recorded in some of the soil samples. Soil pH, OM, K, Ca and Mg mean levels decreased with depth ; Na slightly increased with depth.

Under the natural forests, all the chemical properties followed a similar trend as that observed under teak plantations. Except for Na, as the mean level of these nutrient elements decreased, their corresponding coefficients of variation increased with depth. Again, the high CV's for P in the subsoil resulted from the zero values recorded for some of the soil samples (Table 5). Observed CV values for texture, Db and pH measured in this study suggest that these properties varied less in the topsoil and subsoil under the natural forests. It was further observed that OM content decreased with depth while corresponding CV increased with depth (Table 5)

Dealing with spatial variability in the field is more difficult and more costly because it dictates that more samples must be collected for analysis. Thus it may be appropriate to decrease the confidence level for some of the chemical properties since high variability would make it impossible to collect enough samples to account for differences in soil assessments. The number of samples can be reduced by relaxing the probability level or by increasing the allowable error from (between 10-20%). Correspondingly, the more samples required to estimate soil property means in this study is a reflection of the high variability of some of the properties measured.

The discussion has dealt with the estimation of sample size for given attributes. As in the case of this study, there is always a problem when several measurements are taken from a single sample. Some measurements are bound to be more variable than others. What then should be the basis for sample size determination? The best would be to sample at an intensity great enough to estimate the most variable mean with a predesignated degree of precision. Subsamples can then be taken to estimate those with less variation.

6.0. CONCLUSIONS

This study has shown that the conversion of natural forest sites to teak plantations has modified soil physical and chemical properties which are important to soil productivity and conservation. In summary:

1) Soil OM content and the nutrient status under teak plantation were to a greater extent reduced by conversion of natural forests to teak plantations and possibly nutrient losses through accelerated leaching and soil erosion. Increased soil erosion under teak plantations was most likely caused by the absence of undergrowth vegetation cover and decreases in soil organic matter.
2) Sites converted to teak plantations had less soil N, P, and exchangeable cations concentration and content than soils under the natural forests.
3) Sodium concentration and content was significantly higher in soils under teak plantations but increased with depth under both cover types.
4) Soil pH was nearly neutral and did not significantly differ between soils under teak and natural forests. This indicates that Ca and K levels were lowered proportionally more than Na and Mg under the teak and that an increase of Na in soils under teak helped keep the pH high despite the decrease of the other cations.

The possibility of detrimental changes in nutrient status of soils under teak plantations have major implications in future management decisions. It may be necessary to re-examine more closely the practice of large-scale conversion of natural forests to high value plantation crops. Significant ecological nutrient losses from teak plantations over repeated rotations must be considered in addition to the short term benefits obtained from the high monetary value of teak.

The study also showed soils under teak plantations and natural forests examined to be very variable in most of its physical and chemical properties, making it mandatory to collect more samples to estimate the population means of these properties with a general 95% confidence precision of at least ±10 percent for many of the variables measured. However, the study showed that soils under teak plantations were more variable than soils under natural forests.

This study showed 4-207 samples for topsoil and 13-517 for subsoil would be required tō estimate soil property means with an allowable error of 10 percent at the 95 percent confidence level under teak plantations. Similarly, 9-63 samples for topsoil and 7-296 for subsoil would be required to estimate soil property means with an allowable error of 10 percent at the 95 percent confidence level under natural forests. When the allowable errors were increased from 10 percent to 15 and 20 percent at the same confidence level, sample size required to estimate most of the measured soil properties except available P, exchangeable Mg and Na in some cases were considered more reasonable in terms of resource allocation for sampling and soil analyses.

Data analyses revealed skewness in some of the variables indicating a need for transformation of these variables in order to correct distribution problems before further analyses of data.

The most salient conclusion drawn from this study is that an investigation of soil variability should always form the first stage of a land evaluation project. Although the study of soil variability is laborious and expensive, it would save a considerable amount of time, and effort by enabling wise decisions to be made on sampling procedures and choice of predictive variables for forest site classifications.

7.0. LITERATURE CITED

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APPENDICES

APPENDIX I. SOIL PROPERTIES OF AFRAM FOREST RESERVE (TEAK PLANTATION)

Property	Depth (cm)	Range	Standard error (SE)	Mean	Coefficient of variation (CV%)
N (%)	0-20	0.28-0.10	0.014	0.192	29
P (mgkg^{-1})	0-20	0.00-9.62	0.570	2.399	95
Exch. K (cmol(+)kg^{-1})	0-20	0.11-0.74	0.037	0.249	60
Exch. Ca (cmol(+)kg^{-1})	0-20	4.35-29.60	1.759	10.313	68
Exch. Mg (cmol(+)kg^{-1})	0-20	1.11-3.52	0.156	2.039	31
Exch. Na (cmol(+)kg^{-1})	0-20	0.003-0.062	0.004	0.017	92
pH	0-20	6.08-7.70	0.124	6.87	7
D_b (gcm^{-1})	0-20	0.90-1.46	0.037	1.26	6
OM (%)	0-20	5.30-12.70	0.610	9.32	26
Sand (%)	0-20	47.63-71.70	1.08	61.29	12
Silt (%)	0-20	4.29-34.34	1.80	25.89	28
Clay (%)	0-20	6.62-32.71	1.60	12.82	50
N (%)	20-40	0.04-0.11	0.004	0.073	24
P (mgkg^{-1})	20-40	0.00-1.67	0.104	0.323	129
Exch. K (cmol(+)kg^{-1})	20-40	0.49-0.25	0.014	0.099	57
Exch. Ca (cmol(+)kg^{-1})	20-40	1.65-10.50	0.553	4.472	49
Exch. Mg (cmol(+)kg^{-1})	20-40	0.90-3.15	0.143	1.673	34
Exch. Na (cmol(+)kg^{-1})	20-40	0.005-0.074	0.005	0.025	78
pH	20-40	4.18-7.33	0.237	5.79	16
Db (gcm^{-1})	20-40	1.46-1.90	0.030	1.73	7
OM (%)	20-40	4.20-10.40	0.401	7.34	22
Sand (%)	20-40	38.31-64.90	1.86	47.92	16
Silt (%)	20-40	13.27-42.46	1.75	28.96	24
Clay (%)	20-40	5.54-42.87	1.94	23.11	34

APPENDIX II. SOIL PROPERTIES OF AFRAM FOREST RESERVE (NATURAL FOREST)

Property	Depth (cm)	Range	Standard error (SE)	Mean	Coefficient of variation (CV%)
N (%)	0-20	0.17-0.43	0.019	0.26	29
P (mgkg^{-1})	0-20	0.00-28.42	1.838	9.388	78
Exch. K (cmol(+)kg^{-1})	0-20	0.24-0.74	0.039	0.401	39
Exch. Ca (cmol(+)kg^{-1})	0-20	5.75-31.65	1.788	14.969	48
Exch. Mg (cmol(+)kg^{-1})	0-20	1.53-6.17	0.276	3.327	33
Exch. Na (cmol(+)kg^{-1})	0-20	0.005-0.033	0.002	0.010	60
pH	0-20	5.47-7.72	0.130	7.011	7
D_b (gcm^{-1})	0-20	1.07-1.72	0.044	1.326	13
OM (%)	0-20	5.70-17.20	0.853	9.619	36
Sand (%)	0-20	59.43-79.37	1.37	70.351	8
Silt (%)	0-20	16.91-29.56	0.91	22.437	16
Clay (%)	0-20	3.72-13.04	0.68	7.213	38
N (%)	20-40	0.03-0.57	0.033	0.083	159
P (mgkg^{-1})	20-40	0.00-3.15	0.215	1.005	85
Exch. K (cmol(+)kg^{-1})	20-40	0.02-0.17	0.011	0.087	51
Exch. Ca (cmol(+)kg^{-1})	20-40	0.05-8.25	0.516	3.349	62
Exch. Mg (cmol(+)kg^{-1}).	20-40	0.45-2.85	0.168	1.670	40
Exch. Na (cmol(+)kg^{-1})	20-40	0.00-0.03	0.002	0.011	85
pH	20-40	4.08-6.94	0.228	5.746	16
Db (gcm^{-1})	20-40	1.39-1.81	0.032	1.624	8
OM (%)	20-40	2.90-7.00	0.288	4.219	27
Sand (%)	20-40	50.11-69.54	1.45	61.573	9
Silt (%)	20-40	19.37-42.46	1.06	28.964	18
Clay (%)	20-40	3.58-24.39	1.22	14.69	33

APPENDIX III. SOIL PROPERTIES OF OPRO FOREST RESERVE (TEAK PLANTATION)

Property	Depth (cm)	Range	Standard error (SE)	Mean	Coefficient of variation (CV%)
N (%)	0-20	0.14-1.18	0.064	0.230	111
P (mgkg^{-1})	0-20	0.21-1.61	0.092	0.704	52
Exch. K (cmol(+)kg^{-1})	0-20	0.10-0.76	0.039	0.229	69
Exch. Ca (cmol(+)kg^{-1})	0-20	10.15-20.35	0.73	13.563	21
Exch. Mg (cmol(+)kg^{-1})	0-20	3.37-8.95	0.365	4.964	29
Exch. Na (cmol(+)kg^{-1})	0-20	0.01-0.04	0.002	0.017	49
pH	0-20	5.92-7.56	0.101	6.49	6
D_b (gcm^{-1})	0-20	0.51-1.54	0.060	1.27	19
OM (%)	0-20	10.00-14.60	0.362	12.12	12
Sand (%)	0-20	31.27-52.83	1.45	41.15	14
Silt (%)	0-20	33.29-46.40	0.91	40.00	9
Clay (%)	0-20	12.56-24.60	0.78	18.86	17
N (%)	20-40	0.08-0.17	0.005	0.102	21
P (mgkg^{-1})	20-40	0.00-0.35	0.028	0.065	170
Exch. K (cmol(+)kg^{-1})	20-40	0.09-0.22	0.012	0.128	36
Exch. Ca (cmol(+)kg^{-1})	20-40	5.80-26.90	1.208	10.103	48
Exch. Mg (cmol(+)kg^{-1})	20-40	3.80-9.77	0.393	5.642	28
Exch. Na (cmol(+)kg^{-1})	20-40	0.0003-0.06	0.004	0.29	53
pH	20-40	4.66-6.66	0.180	5.45	13
D_b (gcm^{-1})	20-40	0.58-1.71	0.068	1.39	20
OM (%)	20-40	7.80-13.80	0.367	11.35	13
Sand (%)	20-40	24.19-40.22	1.17	32.33	15
Silt (%)	20-40	27.76-46.37	1.09	37.42	12
Clay (%)	20-40	15.73-37.85	1.34	30.26	18

APPENDIX IV. SOIL PROPERTIES OF OPRO FOREST RESERVE (NATURAL FOREST)

Property	Depth (cm)	Range	Standard error (SE)	Mean	Coefficient of variation (CV%)
N (%)	0-20	0.21-0.41	0.013	0.289	18
P (mgkg^{-1})	0-20	0.00-0.366	0.285	0.920	124
Exch. K (cmol(+)kg^{-1})	0-20	0.14-0.74	0.045	0.361	50
Exch. Ca (cmol(+)kg^{-1})	0-20	12.20-34.45	1.518	20.547	30
Exch. Mg (cmol(+)kg^{-1})	0-20	2.97-6.29	0.229	4.706	20
Exch. Na (cmol(+)kg^{-1})	0-20	0.012-0.03	0.001	0.020	29
pH	0-20	6.56-7.83	0.077	7.39	4
D_b (gcm^{-1})	0-20	0.79-1.60	0.051	1.10	18
OM (%)	0-20	11.80-16.40	0.427	14.30	12
Sand (%)	0-20	37.13-51.35	1.11	47.00	10
Silt (%)	0-20	33.12-43.27	0.69	37.22	7
Clay (%)	0-20	11.70-23.70	0.79	15.78	20
N (%)	20-40	0.06-0.93	0.053	0.138	153
P (mgkg^{-1})	20-40	0.00-0.77	0.060	0.142	168
Exch. K (cmol(+)kg^{-1})	20-40	0.06-0.72	0.040	0.148	109
Exch. Ca (cmol(+)kg^{-1})	20-40	2.21-13.65	0.778	8.141	38
Exch. Mg (cmol(+)kg^{-1})	20-40	1.16-7.18	0.419	4.465	38
Exch. Na (cmol(+)kg^{-1})	20-40	0.02-0.054	0.003	0.030	34
pH	20-40	4.12-7.40	0.220	5.53	16
D_b (gcm^{-1})	20-40	1.14-1.76	0.046	1.57	12
OM (%)	20-40	10.20-15.10	0.370	11.93	12
Sand (%)	20-40	28.66-48.58	1.37	37.38	15
Silt (%)	20-40	25.46-48.29	1.35	32.94	17
Clay (%)	20-40	12.31-39.16	1.69	29.69	23

APPENDIX V. SOIL PROPERTIES OF SOUTH FORMANGSU FOREST RESERVE (TEAK PLANTATION)

Property	Depth (cm)	Range	Standard error (SE)	Mean	Coefficient of variation (CV%)
N (%)	0-20	0.17-0.36	0.014	0.236	24
P (mgkg^{-1})	0-20	0.00-3.00	0.194	0.467	166
Exch. K (cmol(+)kg^{-1})	0-20	0.15-0.58	0.036	0.350	42
Exch. Ca (cmol(+)kg^{-1})	0-20	5.15-28.45	2.014	13.263	61
Exch. Mg (cmol(+)kg^{-1})	0-20	1.43-4.39	0.209	2.515	33
Exch. Na (cmol(+)kg^{-1})	0-20	0.001-0.04	0.002	0.018	44
pH	0-20	5.63-7.70	0.166	6.69	10
D_b (gcm^{-1})	0-20	1.07-1.67	0.040	1.35	12
OM (%)	0-20	9.80-17.00	0.474	12.10	16
Sand (%)	0-20	25.17-57.67	2.28	41.71	22
Silt (%)	0-20	32.91-45.22	1.11	39.12	11
Clay (%)	0-20	9.42-30.82	1.60	19.16	33
N (%)	20-40	0.07-0.15	0.005	0.96	22
P (mgkg^{-1})	20-40	0.00-0.49	0.034	0.048	287
Exch. K (cmol(+)kg^{-1})	20-40	1.43-4.39	0.021	0.132	63
Exch. Ca (cmol(+)kg^{-1})	20-40	1.13-10.20	0.628	4.607	55
Exch. Mg (cmol(+)kg^{-1})	20-40	0.63-3.65	0.187	1.399	53
Exch. Na (cmol(+)kg^{-1})	20-40	0.01-0.04	0.002	0.020	43
pH	20-40	4.31-7.55	0.261	5.81	18
D_b (gcm^{-1})	20-40	1.17-1.92	0.046	1.51	12
OM (%)	20-40	7.60-11.50	0.265	9.83	11
Sand (%)	20-40	15.08-41.00	1.68	26.45	25
Silt (%)	20-40	24.67-41.62	1.16	34.27	14
Clay (%)	20-40	27.08-49.00	1.56	39.54	16

APPENDIX VI. SOIL PROPERTIES OF SOUTH FORMANGSU FOREST RESERVE (NATURAL FOREST)

Property	Depth (cm)	Range	Standard error (SE)	Mean	Coefficient of variation (CV%)
N (%)	0-20	0.26-0.59	0.021	0.387	22
P (mgkg^{-1})	0-20	0.00-8.87	0.585	2.177	108
Exch. K (cmol(+)kg^{-1})	0-20	0.21-0.85	0.037	0.388	38
Exch. Ca (cmol(+)kg^{-1})	0-20	5.00-31.11	1.957	15.469	51
Exch. Mg (cmol(+)kg^{-1})	0-20	1.86-4.89	0.210	3.226	26
Exch. Na (cmol(+)kg^{-1})	0-20	0.01-0.02	0.001	0.012	46
pH	0-20	4.50-7.71	0.232	6.43	14
D_b (gcm^{-1})	0-20	0.69-1.76	0.068	1.07	25
OM (%)	0-20	10.10-16.50	0.472	13.76	14
Sand (%)	0-20	29.91-53.87	1.66	43.70	15
Silt (%)	0-20	33.41-52.17	1.23	40.20	12
Clay (%)	0-20	11.96-22.00	0.74	16.28	18
N (%)	20-40	0.07-0.13	0.004	0.099	16
P (mgkg^{-1})	20-40	0.00-4.54	0.312	0.968	129
Exch. K (cmol(+)kg^{-1})	20-40	0.07-0.41	0.022	0.159	56
Exch. Ca (cmol(+)kg^{-1})	20-40	1.18-6.90	0.393	3.401	46
Exch. Mg (cmol(+)kg^{-1})	20-40	0.65-1.97	0.111	1.191	37
Exch. Na (cmol(+)kg^{-1})	20-40	0.00-0.01	0.001	0.007	58
pH	20-40	3.94-6.93	0.195	5.263	15
D_b (gcm^{-1})	20-40	1.30-2.06	0.043	1.53	11
OM (%)	20-40	6.60-10.00	0.228	8.41	11
Sand (%)	20-40	25.78-50.96	1.54	33.28	19
Silt (%)	20-40	24.75-58.65	2.13	34.94	24
Clay (%)	20-40	11.52-40.96	2.07	31.79	26

APPENDIX VII. COMPARISON OF MEANS AND SIGNIFICANCE LEVELS OF SOIL PROPERTIES UNDER TEAK PLANTATION AND ADJOINING NATURAL FORESTS (AFRAM FOREST RESERVE)

Property	Teak plantation		Natural forests		t-value	Sign. t
	$\bar{X}$ ± CL	SE	$\bar{X}$ ±CL	SE		
			A-HORIZON (0-20CM)			
N (%)	0.192 ± 0.03	0.014	0.26 ± 0.04	0.019	-2.68	0.017
P (mgkg^{-1})	2.399 ± 1.21	0.570	9.388 ± 3.92	1.838	-4.03	0.001
Exch. K (cmol(+)kg^{-1})	0.249 ± 0.08	0.037	0.401 ± 0.08	0.039	-2.63	0.019
Exch. Ca (cmol(+)kg^{-1})	10.313 ± 3.75	1.759	14.969 ± 3.81	1.788	-1.61	0.129
Exch. Mg (cmol(+)kg^{-1})	2.039 ± 0.33	0.156	3.327 ± 0.59	0.276	-3.95	0.001
Exch. Na (cmol(+)kg^{-1})	0.017 ± 0.01	0.004	0.010 ± 0.004	0.002	-1.64	0.121
pH	6.87 ± 0.26	0.124	7.011 ± 0.28	0.130	-0.66	0.521
D_b (gcm^{-1})	1.26 ± 0.08	0.037	1.326 ± 0.09	0.044	-1.01	0.330
OM (%)	9.32 ± 1.30	0.610	9.619 ± 1.82	0.853	-0.27	0.789
Sand (%)	61.29 ± 2.30	1.08	70.35 ± 2.92	1.37	-3.50	0.003
Silt (%)	25.89 ± 3.84	1.80	22.44 ± 1.94	0.91	1.83	0.088
Clay (%)	12.82 ± 3.41	1.60	7.21 ± 1.45	0.68	2.82	0.013
			B-HORIZON (20-40CM)			
N (%)	0.073 ± 0.008	0.004	0.083 ± 0.07	0.033	-0.29	0.777
P (mgkg^{-1})	0.323 ± 0.221	0.104	1.005 ± 0.46	0.215	-2.67	0.018
Exch. K (cmol(+)kg^{-1})	0.099 ± 0.030	0.014	0.087 ± 0.02	0.011	0.63	0.540
Exch. Ca (cmol(+)kg^{-1})	4.472 ± 1.178	0.553	3.349 ± 1.10	0.516	1.29	0.215
Exch. Mg (cmol(+)kg^{-1})	1.673 ± 0.305	0.143	1.670 ± 0.36	0.168	0.01	0.992
Exch. Na (cmol(+)kg^{-1})	0.025 ± 0.011	0.005	0.011 ± 0.004	0.002	2.58	0.021
pH	5.80 ± 0.51	0.237	5.746 ± 0.61	0.228	0.11	0.912
D_b (gcm^{-1})	1.73 ± 0.06	0.030	1.624 ± 0.07	0.032	2.74	0.015
OM (%)	7.34 ± 0.85	0.401	4.22 ± 0.61	0.288	6.29	0.000
Sand (%)	47.92 ± 3.96	1.86	61.57 ± 3.09	1.45	-5.30	0.000
Silt (%)	28.96 ± 3.73	1.75	28.96 ± 2.26	1.06	2.94	0.010
Clay (%)	23.11 ± 4.13	1.94	14.69 ± 2.60	1.22	3.20	0.006

APPENDIX VIII. COMPARISON OF MEANS AND SIGNIFICANCE LEVELS OF SOIL PROPERTIES UNDER TEAK PLANTATION AND ADJOINING NATURAL FORESTS (OPRO FOREST RESERVE)

Property	Teak plantation		Natural forests		t-value	Sign. of t
	$\bar{X}$ ± CL	SE	$\bar{X}$ ± CL	SE		
A-HORIZON (0-20CM)						
N (%)	0.230 ± 0.14	0.064	0.289 ± 0.03	0.013	-0.87	0.400
P (mgkg^{-1})	0.704 ± 0.20	0.092	0.920 ± 0.61	0.285	-0.69	0.503
Exch. K (cmol(+)kg^{-1})	0.229 ± 0.08	0.039	0.361 ± 0.10	0.045	-2.10	0.053
Exch. Ca (cmol(+)kg^{-1})	13.563 ± 1.56	0.73	20.547 ± 3.24	1.518	-3.71	0.002
Exch. Mg (cmol(+)kg^{-1})	4.964 ± 0.78	0.365	4.706 ± 0.49	0.229	0.53	0.606
Exch. Na (cmol(+)kg^{-1})	0.017 ± 0.004	0.002	0.020 ± 0.002	0.001	-1.09	0.293
pH	6.49 ± 0.22	0.101	7.392 ± 0.16	0.077	-6.79	0.000
D_b (gcm^{-1})	1.27 ± 0.13	0.060	1.104 ± 0.11	0.051	2.86	0.012
OM (%)	12.12 ± 0.77	0.362	14.30 ± 0.91	0.427	-3.68	0.002
Sand (%)	41.15 ± 3.09	1.45	47.00 ± 2.37	1.11	-3.90	0.001
Silt (%)	40.0 ± 1.94	0.91	37.22 ± 1.17	0.69	2.42	0.028
Clay (%)	18.86 ± 1.66	0.78	15.78 ± 1.68	0.79	3.40	0.004
B-HORIZON (20-40CM)						
N (%)	0.102 ± 0.01	0.005	0.138 ± 0.11	0.053	-0.66	0.519
P (mgkg^{-1})	0.065 ± 0.06	0.028	0.142 ± 0.13	0.060	-1.17	0.259
Exch. K (cmol(+)kg^{-1})	0.128 ± 0.03	0.012	0.148 ± 0.09	0.040	-0.47	0.642
Exch. Ca (cmol(+)kg^{-1})	10.103 ± 2.57	1.208	8.141 ± 1.66	0.778	1.22	0.243
Exch. Mg (cmol(+)kg^{-1})	5.642 ± 0.84	0.393	4.465 ± 0.89	0.419	1.74	0.102
Exch. Na (cmol(+)kg^{-1})	0.29 ± 0.008	0.004	0.030 ± 0.006	0.003	-0.21	0.839
pH	5.45 ± 0.38	0.180	5.53 ± 0.47	0.220	-0.27	0.794
D_b (gcm^{-1})	1.39 ± 0.14	0.068	1.57 ± 0.10	0.046	-2.11	0.052
OM (%)	11.35 ± 0.78	0.367	11.93 ± 0.79	0.370	-1.09	0.294
Sand (%)	32.33 ± 2.49	1.17	37.38 ± 2.92	1.37	-2.83	0.013
Silt (%)	37.42 ± 2.32	1.09	32.94 ± 2.88	1.35	2.22	0.043
Clay (%)	30.26 ± 2.86	1.34	29.69 ± 3.60	1.69	0.29	0.773

APPENDIX IX. COMPARISON OF MEANS AND SIGNIFICANCE LEVELS OF SOIL PROPERTIES UNDER TEAK PLANTATION AND ADJOINING NATURAL FORESTS (SOUTH FORMANGSU FOREST RESERVE)

Property	Teak plantation		Natural forests		t value	Sign. t
	$\bar{x}$ ± CL	SE	$\bar{x}$ ± CL	SE		
			A-HORIZON (0-20CM)			
N (%)	0.236 ± 0.03	0.014	0.387 ± 0.04	0.021	-5.05	0.000
P (mgkg^{-1})	0.467 ± 0.41	0.194	2.177 ± 1.25	0.585	-2.74	0.015
Exch. K (cmol(+)kg^{-1})	0.350 ± 0.08	0.036	0.388 ± 0.08	0.037	-0.87	0.396
Exch. Ca (cmol(+)kg^{-1})	13.263 ± 4.29	2.014	15.469 ± 4.17	1.957	-0.92	0.374
Exch. Mg (cmol(+)kg^{-1})	2.515 ± 0.45	0.209	3.226 ± 0.45	0.210	-2.38	0.031
Exch. Na (cmol(+)kg^{-1})	0.018 ± 0.004	0.002	0.012 ± 0.002	0.001	3.29	0.005
pH	6.69 ± 0.35	0.166	6.433 ± 0.49	0.232	1.02	0.325
D_b (gcm^{-1})	1.35 ± 0.09	0.040	1.066 ± 0.14	0.068	3.48	0.004
OM (%)	12.10 ± 1.01	0.474	13.756 ± 1.00	0.472	-2.12	0.05
Sand (%)	41.71 ± 4.86	2.28	43.70 ± 3.54	1.66	-0.74	0.473
Silt (%)	39.12 ± 2.37	1.11	40.20 ± 2.62	1.23	-0.68	0.505
Clay (%)	19.16 ± 3.41	1.60	16.28 ± 1.58	0.74	1.58	0.135
			B-HORIZON (20-40CM)			
N (%)	0.096 ± 0.01	0.005	0.099 ± 0.008	0.004	-0.34	0.736
P (mgkg^{-1})	0.048 ± 0.07	0.034	0.968 ± 0.66	0.312	-3.00	0.009
Exch. K (cmol(+)kg^{-1})	0.132 ± 0.04	0.021	0.159 ± 0.05	0.022	-0.85	0.409
Exch. Ca (cmol(+)kg^{-1})	4.607 ± 1.34	0.628	3.401 ± 0.84	0.393	1.58	0.135
Exch. Mg (cmol(+)kg^{-1})	1.399 ± 0.40	0.187	1.191 ± 0.24	0.111	1.00	0.335
Exch. Na (cmol(+)kg^{-1})	0.020 ± 0.004	0.002	0.007 ± 0.002	0.001	4.66	0.000
pH	5.80 ± 0.56	0.261	5.26 ± 0.42	0.195	1.71	0.107
D_b (gcm^{-1})	1.51 ± 0.10	0.046	1.53 ± 0.09	0.043	-0.28	0.786
OM (%)	9.83 ± 0.56	0.265	8.41 ± 0.49	0.228	3.76	0.002
Sand (%)	26.45 ± 3.58	1.68	33.28 ± 3.28	1.54	-2.78	0.014
Silt (%)	34.27 ± 2.47	1.16	34.94 ± 4.54	2.13	-0.31	0.762
Clay (%)	39.54 ± 3.32	1.56	31.79 ± 4.41	2.07	2.63	0.019

APPENDIX X. COMPARISON OF MEAN NUTRIENT CONTENTS AND SIGNIFICANT LEVELS UNDER TEAK PLANTATION AND ADJOINING NATURAL FOREST (AFRAM FOREST RESERVE)

Property	Teak plantation		Natural forests		t value	Sign. of t
	$\bar{x} \pm$ CL	SE	$\bar{x} \pm$ CL	SE		
A-HORIZON (0-20CM)						
N (kgha^{-1})	4865.55	385.31	6891.71	550.78	-2.39	0.031
P (kgha^{-1})	6.18	1.56	24.52	4.88	-4.04	0.001
Exch. K (kgha^{-1})	148.44	37.11	417.09	43.76	-2.61	0.02
Exch. Ca (kgha^{-1})	5204.09	877.95	7932.81	973.93	-1.70	0.110
Exch. Mg (kgha^{-1})	625.86	51.76	1075.87	96.04	-3.49	0.003
Exch. Na (kgha^{-1})	13.17	2.99	8.37	1.27	1.46	0.165
B-HORIZON (20-40CM)						
N (kgha^{-1})	2472.26	153.94	2658.67	1026.10	-0.18	0.857
P (kgha^{-1})	1.08	0.314	3.26	0.701	-2.66	0.018
Exch. K (kgha^{-1})	133.06	19.24	111.79	14.81	0.87	0.398
Exch. Ca (kgha^{-1})	3122.18	398.47	2162.58	329.69	1.60	0.131
Exch. Mg (kgha^{-1})	7.2.90	61.79	658.33	67.78	0.45	0.662
Exch. Na (kgha^{-1})	26.53	5.23	11.01	2.35	2.63	0.019

APPENDIX XI. COMPARISON OF MEAN NUTRIENT CONTENTS AND SIGNIFICANT LEVELS UNDER TEAK PLANTATION AND ADJOINING NATURAL FOREST (OPRO FOREST RESERVE)

Property	Teak plantation		Natural forests		t value	Sign. of t
	$\bar{x} \pm$ CL	SE	$\bar{x} \pm$ CL	SE		
			A-HORIZON (0-20CM)			
N ($kgha^{-1}$)	4407.47	1270.33	6313.89	307.42	-1.30	0.214
P ($kgha^{-1}$)	1.27	0.146	2.13	0.66	-1.26	0.227
Exch. K ($kgha^{-1}$)	173.28	32.34	306.73	40.03	-2.42	0.029
Exch. Ca ($kgha^{-1}$)	5208.46	394.04	8839.08	558.84	-4.82	0.000
Exch. Mg ($kgha^{-1}$)	1162.18	106.68	1237.57	52.04	-0.72	0.483
Exch. Na ($kgha^{-1}$)	9.68	1.43	12.76	0.93	-1.84	0.086
			B-HORIZON (20-40CM)			
N ($kgha^{-1}$)	2823.07	240.11	3900.80	1258.37	-0.82	0.426
P ($kgha^{-1}$)	0.21	0.09	0.4712	0.198	-1.19	0.253
Exch. K ($kgha^{-1}$)	138.74	14.60	172.01	38.45	-0.75	0.463
Exch. Ca ($kgha^{-1}$)	5694.72	869.87	5038.82	471.41	0.59	0.565
Exch. Mg ($kgha^{-1}$)	1874.08	144.45	1680.25	155.93	0.73	0.478
Exch. Na ($kgha^{-1}$)	24.97	3.32	28.19	2.61	-0.77	0.451

APPENDIX XII. COMPARISON OF MEAN NUTRIENT CONTENTS AND SIGNIFICANT LEVELS UNDER TEAK PLANTATION AND ADJOINING NATURAL FOREST (SOUTH FORMANGSU FOREST RESERVE)

	Teak plantation		Natural forests			
Property	$\bar{x} \pm$ CL	SE	$\bar{x} \pm$ CL	SE	t value	Sign. t
			A-HORIZON (0-20CM)			
N (kgha^{-1})	6274.43	328.55	8130.40	547.52	-2.88	0.011
P (kgha^{-1})	1.25	0.481	5.15	1.48	-2.49	0.025
Exch. K (kgha^{-1})	361.18	33.23	313.66	24.50	1.39	0.184
Exch. Ca (kgha^{-1})	6954.57	990.99	6131.18	621.27	0.70	0.496
Exch. Mg (kgha^{-1})	805.61	51.82	832.10	75.38	-0.34	0.741
Exch. Na (kgha^{-1})	14.62	1.73	7.51	1.02	4.33	0.001
			B-HORIZON (20-40CM)			
N (kgha^{-1})	2857.00	140.78	3013.70	178.72	-0.65	0.527
P (kgha^{-1})	0.14	0.095	2.87	0.93	-2.96	0.010
Exch. K (kgha^{-1})	157.94	25.98	189.56	26.96	-0.87	0.400
Exch. Ca (kgha^{-1})	2785.07	388.04	2086.15	246.78	1.54	0.145
Exch. Mg (kgha^{-1})	509.46	68.04	442.30	41.95	0.89	0.389
Exch. Na (kgha^{-1})	18.31	2.15	6.13	0.98	4.37	0.001

APPENDIX XIII. COMPARISON OF MEAN NUTRIENT CONTENTS AND SIGNIFICANT LEVELS UNDER TEAK PLANTATION AND ADJOINING NATURAL FOREST (TOPSOIL AND SUBSOIL)

Property	Teak plantation		Natural forests		t value	Sign. t
	$\bar{x}$ ± CL	SE	$\bar{x}$ ± CL	SE		
			AFRAM			
N (kgha^{-1})	7337.81±982.82	461.20	9550.38±2455.38	1152.36	-1.75	0.100
P (kgha^{-1})	7.26±3.56	1.67	27.78±11.04	5.18	-4.17	0.001
Exch. K (kgha^{-1})	380.16±96.81	45.43	528.87±116.82	54.82	-1.88	0.080
Exch. Ca (kgha^{-1})	8326.27±2374.1	1114.08	10,095.39±2576.7	1209.15	-0.86	0.403
Exch. Mg (kgha^{-1})	1328.76±183.65	86.18	1734.2±308.09	144.58	-2.14	0.049
Exch. Na (kgha^{-1})	39.69±11.66	5.47	19.38±6.27	2.94	3.21	0.006
			OPRO			
N (kgha^{-1})	7230.54±2713.23	1273.22	10,1214.7±2921.22	1370.82	-1.45	0.166
P (kgha^{-1})	1.48±0.403	0.189	2.60±1.69	0.79	-1.36	0.194
Exch. K (kgha^{-1})	312.02±93.34	43.80	478.74±143.18	67.19	-1.86	0.082
Exch. Ca (kgha^{-1})	10,903.13±2389.85	1121.47	13,877.9±1698.24	796.92	-1.80	0.092
Exch. Mg (kgha^{-1})	3036.26±474.1	222.48	2917.82±387.71	181.94	0.34	0.736
Exch. Na (kgha^{-1})	34.65±8.72	4.09	40..95±5.69	2.67	-1.32	0.206
			SOUTH FORMANGSU			
N (kgha^{-1})	9131.43±726.88	341.10	11144.1±1363.61	639.89	-2.43	0.028
P (kgha^{-1})	1.39±1.09	0.51	8.01±4.51	2.15	-3.07	0.008
Exch. K (kgha^{-1})	519.12±100.39	47.10	503.22±84.69	39.74	0.31	0.764
Exch. Ca (kgha^{-1})	9739.65±2731..41	1281.75	8267.33±1534.38	720.03	1.01	0.330
Exch. Mg (kgha^{-1})	1315.07±241.63	113.39	1274.4±183.95	86.32	0.30	0.772
Exch. Na (kgha^{-1})	32.93±6.46	3.03	13.64±3.01	1.41	5.33	0.000

APPENDIX XIV. PHYSICAL AND CHEMICAL PROPERTIES OF SOILS UNDER TEAK PLANTATIONS (AFRAM, OPRO AND SOUTH FORMANGSU FOREST RESERVES).

Property	Range	Mean ($\bar{x}$)	(SD)	CV%	No. of samples* n_1	n_2	n_3
		(0-20 CM)					
N (%)	0.098-1.18	0.22 ± 0.04	0.15	69	189	84	48
P (mg kg^{-1})	0.00-9.62	1.19 ± 0.46	1.63	137	718	320	180
Exch. K (cmol(+)kg^{-1})	0.103-0.76	0.28 ± 0.04	0.16	57	125	56	33
Exch. Ca (cmol(+)kg^{-1})	4.35-29.60	12.38 ± 1.86	6.44	52	107	49	29
Exch. Mg (cmol(+)kg^{-1})	1.11-8.95	3.17 ± 0.48	1.64	52	106	47	29
Exch. Na (cmol(+)kg^{-1})	0.003-0.062	0.02 ± 0.0002	0.01	64	161	72	42
pH	5.63-7.70	6.69 ± 0.16	0.54	8	4	2	1
OM (%)	5.30-17.0	11.18± 0.68	2.34	21	20	10	6
D_b (g cm^{-3})	0.51-1.67	1.30 ± 0.06	0.19	14	11	6	3
Sand (%)	25.17-71.7	48.05 ± 3.46	11.98	25	27	14	9
Silt (%)	4.29-46.4	35.00 ± 2.4	8.34	24	25	13	8
Clay (%)	5.58-33.89	16.95 ± 1.78	6.16	36	52	25	15
		(20-40 CM)					
N (%)	0.04-0.17	0.09 ± 0.0002	0.02	26	30	15	9
P (mg kg^{-1})	0.00-1.67	0.15 ± 0.08	0.28	195	1470	667	375
Exch. K (cmol(+)kg^{-1})	0.049-0.372	0.12 ± 0.02	0.06	54	114	51	31
Exch. Ca (cmol(+)kg^{-1})	1.13-26.90	6.39 ± 1.22	4.25	66	174	77	44
Exch. Mg (cmol(+)kg^{-1})	0.63-9.77	2.90 ± 0.64	2.22	76	229	102	58
Exch. Na (cmol(+)kg^{-1})	0.0003-0.074	0.20 ± 0.0002	0.02	62	149	68	38
pH	4.18-7.55	5.68 ± 0.26	0.91	16	13	7	5
OM (%)	4.20-13.80	9.51 ± 0.62	2.16	23	23	12	8
Db (g cm^{-3})	0.58-1.92	1.55 ± 0.08	0.24	16	12	7	5
Sand (%)	15.08-64.90	35.56 ± 3.2	11.09	31	40	19	12
Silt (%)	13.27-46.37	33.55 ± 1.86	6.41	19	17	9	6
Clay (%)	5.54-49.0	30.97 ± 2.7	9.32	30	38	18	11

*Estimate of the number of samples to achieve: n_1 ($\bar{X}$) ± 10% with 95%, n_2 ($\bar{X}$) ± 15% with 95% confidence and n_3 ± ($\bar{X}$) 20% with 95% confidence.

APPENDIX XV. PHYSICAL AND CHEMICAL PROPERTIES OF SOILS UNDER NATURAL FORESTS (AFRAM, OPRO AND SOUTH FORMANGSU FOREST RESERVES).

Property	Range	Mean ($\bar{x}$)	(SD)	CV%	No. of samples*		
					n_1	n_2	n_3
		(0-20 CM)					
N (%)	0.17-0.79	0.31 ± 0.02	0.09	29	34	17	11
P (mg kg^{-1})	0.00-28.42	4.16 ± 1.68	5.80	139	762	338	191
Exch. K (cmol(+)kg^{-1})	0.136-0.851	0.38 ± 0.04	0.16	42	68	32	19
Exch. Ca (cmol(+)kg^{-1})	5.0-34.45	16.99 ± 2.12	7.36	43	75	35	21
Exch. Mg (cmol(+)kg^{-1})	1.53-6.30	3.75 ± 0.34	1.16	31	40	19	12
Exch. Na (cmol(+)kg^{-1})	0.005-0.033	0.01 ± 0.0002	0.01	50	98	44	27
pH	4.50-7.83	6.95 ± 0.22	0.74	11	9	3	2
OM (%)	5.70-17.20	12.53 ± 0.92	3.20	26	28	14	9
D_b (g cm^{-3})	0.69-1.76	1.17 ± 0.08	0.24	21	20	11	7
Sand (%)	29.91-52.17	53.90 ± 3.8	13.18	25	26	13	9
Silt (%)	3.72-23.7	13.09 ± 1.48	8.67	26	29	14	10
Clay (%)	7.32-41.36	21.14 ± 2.4	5.10	39	60	29	18
		(20-40 CM)					
N (%)	0.033-0.93	0.11 ± 0.04	0.14	135	711	317	177
P (mg kg^{-1})	0.00-4.54	0.71 ± 0.28	0.95	135	719	320	179
Exch. K (cmol(+)kg^{-1})	0.017-0.718	0.13 ± 0.04	0.11	85	285	127	72
Exch. Ca (cmol(+)kg^{-1})	0.05-13.65	4.96 ± 0.94	3.22	65	166	74	42
Exch. Mg (cmol(+)kg^{-1})	0.45-7.18	2.44 0.52	1.80	74	213	95	54
Exch. Na (cmol(+)kg^{-1})	0.00003-0.054	0.02 ± 0.00002	0.01	82	264	118	66
pH	3.94-7.40	5.51 ± 0.24	0.86	16	12	7	5
OM (%)	2.90-15.10	8.19 ± 0.98	3.39	42	68	30	19
Db (g cm^{-3})	1.14-2.06	1.57 ± 0.04	0.16	10	7	2	2
Sand (%)	25.78-69.54	44.08 ± 4	13.84	31	39	20	12
Silt (%)	19.37-58.65	30.54 ± 2.28	7.90	26	29	14	9
Clay (%)	3.58-40.96	25.39 ± 2.94	10.17	40	63	30	18

*Estimate of the number of samples to achieve: n_1 ($\bar{X}$) ± 10% with 95%, n_2 ($\bar{X}$) ± 15% with 95% confidence and n_1 ± ($\bar{X}$) 20% with 95% confidence.

APPENDIX XVI. COMPARISON OF MEANS OF SOIL MACRO-NUTRIENT CONTENTS OF THE 0-20 AND 20-40 CM DEPTHS UNDER TEAK PLANTATIONS AND ADJOINING NATURAL FORESTS (AFRAM, OPRO AND SOUTH FORMANGSU FOREST RESERVES).

	Teak plantation			Natural forest		
Property	Range	($\bar{x}$)	SD	Range	($\bar{x}$)	SD
(0-20 CM)						
N (kg ha^{-1})	1333.58-11468.09	4743.17 ± 692.84	2400.07	1122.82-23291.15	3296.40 ± 1101	3813.94
P (kg ha^{-1})	0.003-80.27	10.59 ± 4.54	15.43	0.0012-10.06	1.58 ± 0.6	2.07
K (kg ha^{-1})	68.12-787.82	265.75 ± 52.12	180.57	18.06-588.69	141.27 ± 26.14	90.53
Ca (kg ha^{-1})	1074.61-17.237.86	5419.69 ± 1062.74	3681.46	31.95-17,941.22	4355.24 ± 801.4	2776.15
Mg (kg ha^{-1})	355.60-2042.95	801.54 ± 99.88	345.99	193.81-3517.38	1231.53 ± 191.96	664.95
Na (kg ha^{-1})	1.79-76.79	16.02 ± 4.6	15.93	0.028-52.56	15.22 ± 3.46	11.99
(20-40 CM)						
N (kg ha^{-1})	1927.42-22732.92	5496.38 ± 931.84	3228.01	2154.73-12431.25	4667.03 ± 812.62	2154.73
P (kg ha^{-1})	0.002-8.133	1.28 ± 0.58	2.01	0.002-19.63	4.463 ± 1.288	4.46
K (kg ha^{-1})	71.16-686.63	279.98 ± 48.16	166.82	68.13-500.51	220.39 ± 35.16	121.81
Ca (kg ha^{-1})	1551.24-14237.04	6944.16 ± 922.08	3194.15	693.55-9566.36	3684.14 ± 725.6	2513.55
Mg (kg ha^{-1})	495.56-2694.16	1241.14 ± 153.28	530.96	240.43-2694.16	594.62 ± 87.18	302.00
Na (kg ha^{-1})	6.86-57.12	18.52 ± 2.94	10.15	0.030-39.86	10.65 ± 2.32	8.00

APPENDIX XVII. COMPARISON OF MEANS OF SOIL MACRO-NUTRIENT CONTENTS OF THE (TOPSOIL+SUBSOIL) HORIZONS UNDER TEAK PLANTATIONS AND ADJOINING NATURAL FORESTS (AFRAM, OPRO AND SOUTH FORMANGSU FOREST RESERVES).

Property	Teak plantation			Natural forest		
	Range	($\bar{x}$)	SD	Range	($\bar{x}$)	SD
N (kg ha^{-1})	4192.47-26024.49	7899.93 ± 945.8	3276.37	4941.40-30419.28	10,303.06 ± 1255.12	4347.83
P (kg ha^{-1})	0.01-29.34	3.38 ± 1.4	4.84	0.01-83.54	12.80 ± 4.86	16.84
K (kg ha^{-1})	156.04-934.17	403.77 ± 57.18	198.11	213.49-1352.5	503.61 ± 62.52	216.55
Ca (kg ha^{-1})	3695.58-25994.94	9656.35 ± 1362.7	4720.51	2808.97-21650.64	10,746.87 ± 1256.02	4350.96
Mg (kg ha^{-1})	787.61-5682.05	1893.36 ± 292.02	1011.62	618.41-3901.32	1975.47 ± 258.72	896.26
Na (kg ha^{-1})	9.78-88.44	35.76 ± 4.94	17.13	5.85-66.13	24.67 ± 4.4	15.23

APPENDIX XVIII. FIELD DESCRIPTION OF SOIL PROPERTIES UNDER TEAK/NATURAL FOREST PAIRS.

Location	Cpt.	Cover type	Depth (cm)	Soil matrix colour	Texture class	Structure[z]	Consistence[y]	Boundary[x]	Rooting[w]	Db (g cm^{-3})	Species composition of native forest
Afram	4	Teak	0-20	5YR3/1 very dark grey	LS	wgr	fr	d	f fine roots	1.26	
			20-40	5YR4/4 reddish brown	L	msbk	fi	c	p coarse roots	1.73	
		Natural forest.	0-20	5YR2.5/2 dark reddish brown	SiS	wgr	fr	c	vp fine roots	1.33	*Aningeria robusta*, *Mansonia altissima*, *Melicia excelsa* (Odum), *Anogeissus* spp., *Afzelia spp*
			20-40	7.5 YR5/6 strong brown	SL	wsbk	fi	c	m coarse roots	1.62	
Opro	17	Teak	0-20	5YR2.5/2 dark reddish brown	L	mg	fr	c	m coarse roots	1.27	
			20-40	5YR3/4 dark reddish brown	CL	msbk	fi-fr	g	f coarse roots	1.39	
		Natural forest.	0-20	5YR2.5/1 black	L	fgr	fr	d	vp fine roots	1.10	*Entandrophragma spp*, *Afzelia bella*, *Ceiba pentandra*, *Celtis spp*, *Terminalia superba*, *Antiaris africana*, *Sterculia spp*
			20-40	5YR4/4 reddish brown	CL	mgr	fr-fi	c	p fine roots	1.57	
South Formangsu	4	Teak	0-20	2.5YR3/4 dark reddish brown	L	mgr	fi	c	m coarse roots	1.35	
			20-40	10YR3/6 dark red	CL	ssbk	fi	g	f coares roots	1.51	
	7	Natural forest.	0-20	5YR3/4 dark reddish brown	L	mgr	fr	c	vp fine roots	1.07	*Terminalia superba*, *Terminalia ivorensis*, *Melicia excelsa*, *Triplochiton scleroxylon*, *Ceiba pentandra*, *Entandrophragma spp*, *Pynanthus angolensis*
			20-40	2.5YR3/6 dark red	CL	msbk	fi	g	vp coarse roots	1.53	

[z] c = coarse, m = medium, f = fine; 1 = weak, 2 = moderate, 3 = strong; gr = granular, sbk =subangular blocky, * = structureless.

[y] d = dry, fi = firm, fr = friable, vfr = very friable, m = moist, l = loose

[x] d = diffuse, a = abrupt, c = clear, g =gradual , dt = distinct

[w] v = very, f = few, m = moderate, p = plentiful

Cpt = compartment