Physico-Chemical Properties of Soil in The High Forest Zone of Ghana Associated with Logged Forest and with Areas Converted to Teak (*Tectona grandis* Linn. F)

By

Francis K. Salifu

A Graduate Thesis Submitted
In Partial Fulfilment of the Requirements
for the Master of Science in Forestry Degree

Faculty of Forestry
Lakehead University
1997

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ABSTRACT

Salifu, K. F. 1997. Physico-chemical properties of soils associated with logged forest and areas converted to teak (*Tectona grandis* Linn. F). M.Sc.F thesis, Faculty of Forestry, Lakehead University, Thunder Bay. 104 pp. Major advisor Dr. W. L. Meyer.

Keywords: *Tectona grandis* Linn. F, logged forest, physico-chemical properties, total nutrients, nutrient concentration, regression analysis.

The rapid and extensive introduction of teak to satisfy a predicted wood shortage in Ghana has given rise to the question of the short/long-term effects that management of teak plantations might have on soil properties. No research data is currently available to answer this question.

Physico-chemical properties of soils were compared under two distinct forest covers (logged native forest, and teak plantations) at three different forest reserves (Bosomoa, Tain II and Yaya) located in the Kintampo, Dormaa - Ahenkro, and Sunyani Forest Districts, respectively in The High Forest zone of Ghana. One-Way analyses of variance (ANOVA) was used for the comparisons. Ages of the plantations used for the study ranged from 15 to 29 years. A total of 28 [20m x 20m] random sample plots representing 14 teak/logged forest pairs were included in the study. Three hundred fifty (350) soil samples were collected in June, 1997 and analyzed for their physico-chemical properties.

Within the Bosomoa and Yaya locations, nitrogen (N), and magnesiumn (Mg) concentrations and organic matter (OM) contents in the surface soil horizons were significantly higher under logged forest than under teak plantations. Also phosphorus (P) and potassium (K) concentrations were significantly higher under logged forest at Bosomoa. Similarly, total nutrients were generally higher 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 forest was due to more undergrowth, litter and organic matter under logged forest. Higher nutrients under logged forest may also be due to a lesser demand for these nutrients by tree species in logged forest. Lower soil macro-nutrient concentration and contents in soils under teak was due to lower organic matter content under teak cover. Lower nutrients in soils under teak plantations may also be associated with higher nutrient demand, and nutrient immobilization by teak. At the Tain II sites, there were no significant differences among soil nutrient concentrations and contents under teak and native logged forest. Soil exposure due to bush fires at Bosomoa sites resulted in higher surface soil horizon bulk densities (Db's) under teak plantation (1.33 g cm^{-3}). In contrast, surface soil horizon Db's under teak plantation were lower at Tain II (1.23 g cm^{-3}) and at Yaya sites (1.10 g cm^{-3}). There were no significant differences in Db's between vegetation types within locations.

Regression models were developed for Db of soils under teak cover, using easily measurable soil variables such as OM, Clay, silt, volume of coarse fragments and soil pH. Equations relating Db of soils under teak cover to these soil variables are presented for Bosomoa and Tain II. The models can be used to explain Db at the study locations and on comparable sites.

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ACKNOWLEDGMENTS

I wish to acknowledge the guidance, support and constructive suggestions of Dr.W.L. Meyer, my major advisor, and Dr. K.M. Brown and Dr. W.H. Carmean the other members of my graduate committee, and Dr. E.Y. Sarfo my External Examiner.

I acknowledge the contribution of E. Ashadu, Boachie-Yaadom and Y. Diabore, all Technical Officers of the Forestry Department of Ghana for their assistance during field data collection. Thanks to the Forest Guards and C. Peprah our great driver. I also wish to thank the Forestry Department, Ghana, for providing the plantations for this study.

My sincere thanks to Dr. A. Nyamekye of the Savanna Agricultural Research Institute (SARI) and his technical staff, and to G.W. Vanson and the technical staff at the Lakehead University's Instrumentation Laboratory for their help in laboratory analysis of the research data.

I am indebted to the Canadian International Development Agency (CIDA) for funding my graduate studies and this thesis, and also to each and every one at the Faculty of Forestry at Lakehead University for their assistance in one way or the other.

To my colleagues from Ghana, I have enjoyed the inspiration, support and fun that we had together.

September, 1997

F.K.S.

DEDICATION

To

Francisca, and my **brothers** and **sisters** with love

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1.0 INTRODUCTION

In the late 1960's projections of timber production in Ghana indicated that the native forest would not be able to meet all the country's long-term timber requirements. In 1968, the Food and Agriculture Organization (FAO) responded to this concern and proposed the establishment of a national forest plantation estate that commenced with the establishment of 5,000 ha teak (*Tectona grandis* Linn. F), *Gmelina arborea* Linn. and *Cedrela odorata* plantations in The High Forest zone of Ghana (FAO/UNEP 1981). The estate was eventually increased to approximately 50,000 ha of plantations (Forestry Department 1993). Teak currently occupies about 10,000 ha of the national plantation estate (Forestry Dept. 1994).

Doubts about the capacity of native forest to meet domestic demand and export timber requirements became even more apparent in the 1990's. In Ghana, as in other African countries, there is a general perception that industrial scale plantations are needed to help alleviate future wood demand. This need is set against the background of rapidly expanding demand for timber products, and the decreasing roundwood supply available from natural forest both within Ghana (Figure 1, Forestry Dpt. 1993), and for the world (Figure 2, Nambiar 1984).

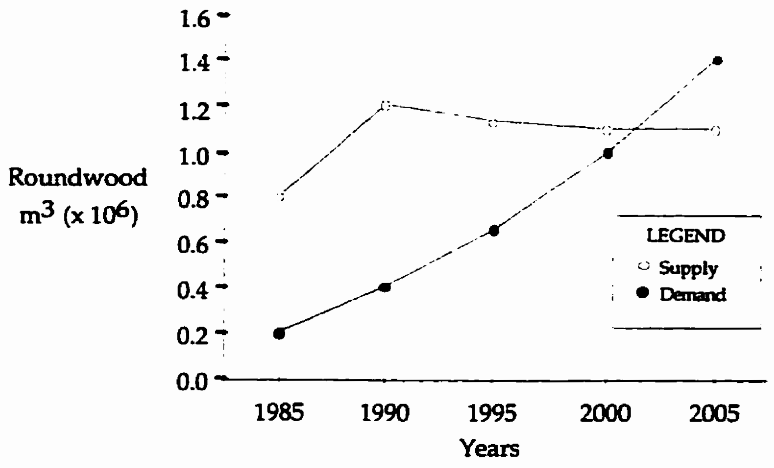

Figure 1. Ghanaian native forest log supply and domestic demand (Forestry Dpt.1993).

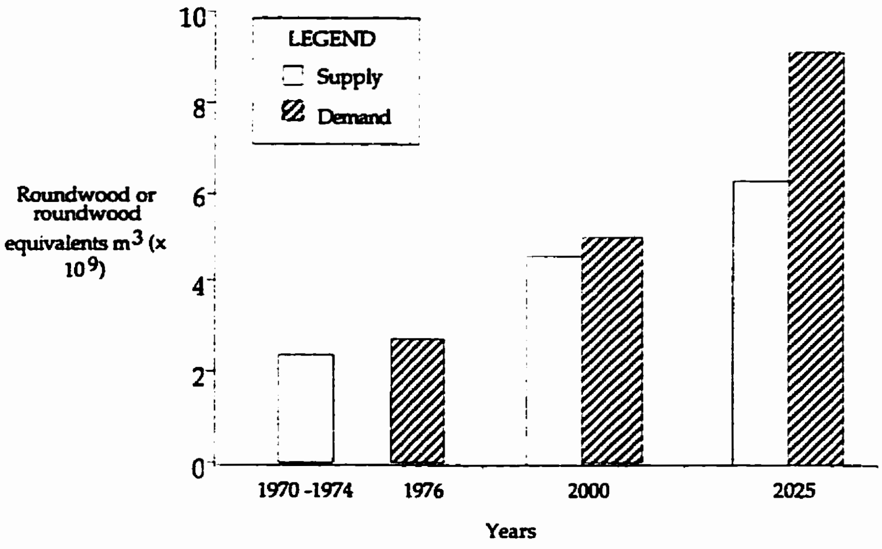

Figure 2. World wood supply and demand (Nambiar 1984).

In view of this shortfall of wood supply, the goal of the Forestry Department is to establish a productive plantation estate of up to 200,000 ha within 40 years using annual planting programmes of 5,000 ha. This plantation strategy is designed to maintain self sufficiency in timber products as well as to maintain continued exports (Forestry Dept. 1993). The plantation strategy was designed to:

1) create a plantation forest estate for the commercial production of large volumes of timber,
2) create a financially viable industry by planting fast growing, high yielding, high value species of proven performance,
3) arrest environmental degradation on large sized forest reserves by bringing deforested areas of reserves back into productive use, and to protect residual natural forest from further damage,
4) ensure that communities near the plantations benefit from the area's development, and
5) promote community planting on small scale and to also improve areas of secondary and degraded natural forest .

The preferred tree species for meeting these objectives has been teak. Because of the rapid economic returns from teak plantations, companies (*e.g.*, Pioneer Tobacco Co. Ltd., Ashanti Goldfields Co), Non-Governmental Organizations (NGOs), and individuals have also been motivated to establish large plantations of this tree species.

The rapid and extensive introduction of teak has given rise to the question of what the short/long-term effects of teak plantations and of management methods might have on soil properties in Ghana.

Previous studies suggest that when large areas of native forest are converted into plantations of fast growing, short rotation exotic tree crops, the effects may include: 1) a change in soil physico-chemical properties associated with tree planting (Alexander *et al.* 1981, Hase and Foelster 1983, Prasad *et al.* 1985, Totey *et al.* 1986, Aborisade and Aweto 1990, Bhoumik and Totey 1990, George and Varghese 1992); 2) nutrient immobilization (Aborisade and Aweto 1990, George and Varghese 1992); 3) nutrient loss through harvest (McColl and Powers 1984, Aborisade and Aweto 1990); and 4) nutrient loss from leaching and erosion (McColl and Powers 1984, Aborisade and Aweto 1990).

No research data is currently available to address the above concerns. There is, therefore, a considerable need to assess already existing teak plantations for their potential long-term effects on soil properties before, introducing teak on large scale industrial plantations. Such information will enhance the use of appropriate silviculture and management techniques to sustain productivity of future teak plantations.

Moreover, increased worldwide recognition of possible decrease in productivity of forest sites has led to quantitative estimates of nutrient exports for several temperate forest ecosystems during the last decade (Hase and Foelster 1983). However, such data are still very rare for tropical forests and despite increasing teak planting in Ghana, no research work has been carried out to determine the long-term effects of teak on the ecosystem.

Also, several theories with regard to soil changes under pure teak plantations have been suggested (Aborisade and Aweto 1990, Bhoumik and Totey 1990, George and Varghese 1992), but it is apparent that much quantitative data are required to prove or disprove a hypothesis of soil deterioration.

The goal of this research work is to provide insights to long-term effects of teak plantations, and of teak plantation management systems on soil physico-chemical properties in Ghana.

The specific objectives of this study were to:

1) provide reference material on soils under teak management,
2) quantify and compare selected soil physico-chemical properties of paired teak/adjacent native logged forest, growing on similar soils.
3) model bulk density (Db; g cm^{-3}) under teak plantations using soil particle size distribution, organic matter content (OM, %), volume of coarse fragments (Vcf) and soil pH as predictor variables.

The study had the following limitations:

1) Base line soil data were not available to compare with the data of this study.
2) Data were based on only soil properties under teak/logged forest pairs. Data on foliar nutrient concentrations and contents to compare with soil data, could have provided strong evidence in support of conclusions with regard to nutrient immobilization by teak.
3) The effects of teak plantation management practices were confounded with

the effects of teak on soil chemistry. Therefore, the lower nutrients under teak plantations could have been due to site preparation and to soil exposure during conversion of native logged forest to teak plantations, and to nutrient exports in biomass associated with thinning.

2.0 LITERATURE REVIEW

2.1. HABITAT CONDITIONS AND LIFE HISTORY

Properties and Uses

Teak is a broad-leaved deciduous tree belonging to the family *Verbenaceae* and is one of the most valuable and cultivated exotic tree species in the tropics (Borota 1991, Drechsel and Zech 1994). The timber of teak is durable, hard, strong, and resistant to vermin. Teak has been used for ship building, dwelling construction, bridges, railway carriages and sleepers, luxury furniture, decorative veneer, wood carving, and fuelwood (Borota 1991, Mbuya *et al.* 1994). Teak has also been used for the treatment of menstrual disorders and haemorrhage, and as a dye (White 1991).

2.1.1. Habitat Conditions

Range

Teak is native to India, Burma, Thailand, and Laos (Keogh 1987, Figure 3). As an exotic, teak is grown mainly in Bangladesh, Cambodia, Malaysia, Nigeria, Ghana, and Liberia (Hedegart 1976, FAO/UNEP 1981, Aborisade and Aweto 1990, Zech and Drechsel 1991). Teak was first introduced into Ghana from unknown source in 1905 by the German Administration (Troup 1921, Kadambi 1972). Latter introductions were from Trinidad (Troup 1921).

Climate

The most favourable growth conditions for teak exist in those tropical climates which have an annual precipitation of 1,250 mm to 1,800 mm and a more or less uniform temperature with a minimum of 12°C and a maximum of 38°C (Hedegart 1976, Borota 1991). Hedegart (1976) further observed that teak can grow in areas with rainfall ranging from as low as 600 mm (*e.g.*, Togo) to as high as 4000 mm (*e.g.*, Bangladesh).

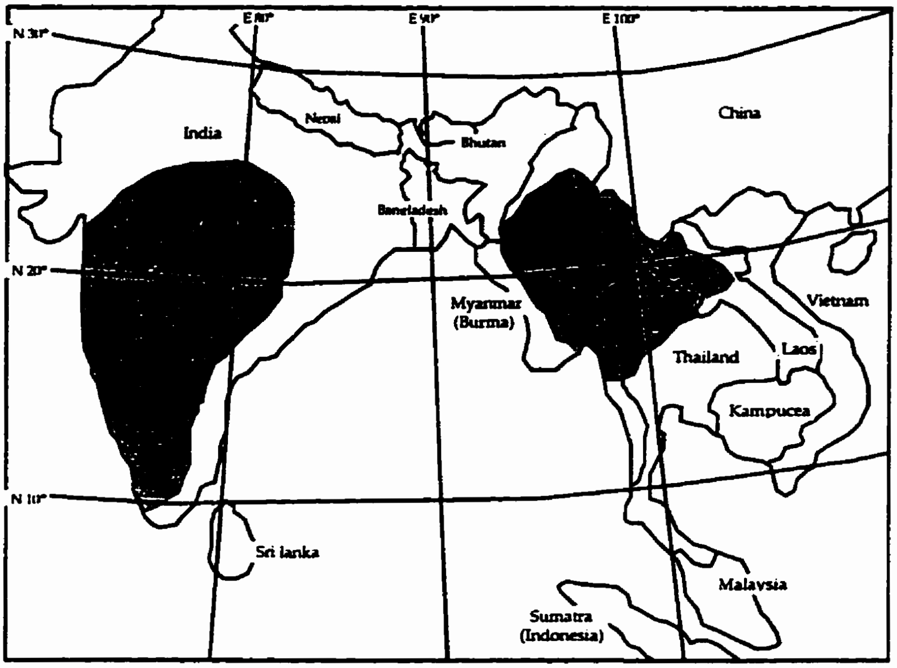

Figure 3. Natural range of teak in Asia (adapted from Weaver 1993).

Soils and Topography

Teak will grow and survive in a wide range of edaphic conditions. It requires well drained sandy loam soils that are mildly acidic to neutral in the topsoil (Hedegart 1976, Bhoumik and Totey 1990). Teak does well on parent material derived from gneiss, granite, slates, and other metamorphic rocks as well as on tertiary sand and limestone (Seth and

Yadav 1959, Singh *et al.* 1986, Borota 1991). However, teak is not widespread on lateritic soil, in maritime tidal regions, or in evergreen wet tropical forests with high rainfall. Similarly, dry hill tops and wet depressions are unproductive sites for teak (White 1991, Zech and Drechsel 1991). Teak grows in natural habitat at altitudes ranging from 800 m to 1300 m above mean sea level (Hedegart 1976), elevations in excess of 1000 m have been found to negatively influence teak growth (Weaver 1993). Furthermore, soil compaction, and heavy clays with low contents of Ca and Mg limits teak growth (Streets 1962). Teak has also been shown to be sensitive to phosphate deficiency (Murray 1961).

Associated Vegetation in Native Range

In parts of the native range of teak, such as in India, the presence of bamboos, especially, *Dendrocalamus strictus* is regarded as an indication of suitable teak sites. Indicators of unsuitable sites for teak are: *Imperata* grass, preponderance of *Xylia*, stunted *Anogeissus latifolia*, abundant *Terminalia tomentosa*, and presence of canes and *Alpinia* (White 1991).

Generally, teak is not considered to be a good soil improver and it is advantageous to introduce remunerative underwood species under teak plantations (White 1991). Suggested cover crops include: *Leucaena glauca* in a mixture with jungle growth, *Tephrosia, Idigofera, Crotalaria, Mimosa, Desmodium, Phaseolus, Dolichos, Centrosema, Clitoria*, Cotton, Bamboo, Tapioca, Ginger and Chilli (White 1991).

2.1.2 Life History

Regeneration and Growth

Teak plantations are more often established using stumps because direct sowing of seeds does not always give satisfactory results (Borota 1991). Direct showing, the oldest method, is characterized by a higher mortality and slow growth (Weaver 1993). Stumps may be produced when required and transported over considerable distances while maintaining their viability. Moreover, stumps are easier to plant, and subsequent growth is more rapid and vigorous (Weaver 1993).

Teak has rapid growth in Nigeria when young, but the overall growth rate on longer timber rotations (Aborisade and Aweto 1990), is not outstanding. Fifty-year Indian yield tables allow for 80-year rotation (FAO 1956), Borota (1991), noted that the rotation for obtaining logs of good quality is usually around 70 to 80 years. Timber volume predicted from yield tables on the first site class at 80 years, was 340 m^3 per hectare (Borota 1991).

Heights of 35 m and diameters of 70 cm in 46 year-old teak have been reported in Madhya Pradesh, India (Bhoumik and Totey 1990). Similarly, in Southern India Ventatramana and Tireman (Borota 1991) reported that the greatest height of a teak tree and largest diameter in 60 years growth were 58 m and 245 cm, respectively. Early height growth averaged between 1.3 to 2 m in Ghana (Troup 1921).

For more detailed information on regeneration and growth of teak, readers are encouraged to consult (Keogh 1987, White 1991, Weaver 1993).

Nutrition and Growth

Drechsel and Zech (1994) evaluated teak mineral nutrition and effects of nutrition and site quality on teak growth in West Africa using a Diagnosis and Recommendation Integrated System (DRIS). The objective of the investigation was to study the site variables controlling teak yield and to establish guidelines for the selection of high productive sites in Benin, Ivory Coast, Liberia, Nigeria, and Togo. Drechsel and Zech (1994) found that nitrogen (N) nutrition, rooting depth and precipitation were the most important variables influencing teak growth in West Africa. Nitrogen deficiency indicated by both foliar and soil N on all soils except Vertisols was significantly less ($r = 0.8 - 0.9$, $p < 0.01$) on poor levels of site index (SI). Besides N, Drechsel and Zech (1994) also believed P and Ca to influence teak growth in a positive manner. The minimum nutrient requirements for a 15 years old teak plantation was estimated in Nigeria (Nwoboshi 1984). Nitrogen, P, K, Ca and Mg requirements in kilogram per hectare were 328, 76, 556, 357 and 62, respectively (Nwoboshi 1984).

Nitrogen and P are among the most crucial nutrients for teak growth in the tropics. However, soil N is usually deficient and nitrogen's availability has been found to vary with season (Ahn 1962, Young 1976). Furthermore, it was observed that total nitrogen (N_t) increased with increasing rainfall at the beginning of the rainy season after which quantities present were again reduced by leaching and plant absorption (Ahn 1962, Young 1976). In the tropics, phosphorus (P) is often in the shortest supply (Ahn 1962), probably due to high P fixation under strong acid conditions as well as in soils rich in iron and aluminum oxides (Young 1976). In such cases P fixation lowered available P thereby restricting root and plant growth.

Reaction to Competition

Teak is generally a light demanding tree species and needs full sunlight for good growth (Borota 1991). Interplanting, therefore, requires management to ensure that teak is not overtopped by competing vegetation (Keogh 1987, White 1991). Briscoe and Ybarra-Coronado (1971) found that removal of competitor species from a teak stand resulted in 53% increase in basal area (BA) growth compared to a non-released stand in Puerto Rico. According to Troup (1921), teak was overshadowed by *Gmelina arborea* in Nigeria and Sierra Leone.

2.2. PLANTATION REQUIREMENTS AND THE *TAUNGYA* SYSTEM

Perhaps the best reason for plantation establishment is to increase forest areas so as to relieve the pressure to exploit the dwindling reserves of natural forest in the world (Evans 1992). Westoby (1989) anticipates that the rapidly increasing interest in plantation forestry in the tropics will play a vital role in future world wood supply. Despite the argument by Evans (1992) that there was no immediate biological shortage of timber on a global scale since present increment of wood (1.1 $m^3 ha^{-1} yr^{-1}$) exceeded present consumption (0.85 $m^3 ha^{-1} yr^{-1}$), increasing world population and economic growth will likely result in a possible demand for wood in excess of overall supply by the end of this century Figure 2 (Nambiar 1984). Clearly, relieving the relentless pressure on the dwindling natural forest resources and meeting anticipated future demands for wood in an environmentally sound and sustainable basis will require effective and efficient large scale plantation establishment, and site specific management.

According to Nwoboshi (1984) the need to maximize the amount of wood produced per unit area is now widely appreciated in the tropics, and has brought about rapid replacement of natural forests with fast growing and higher yielding tree plantations by a *taungya* system.

The *taungya* (Burmese for hill cultivation) system has been the most important means of afforestation in the tropics since 1910 (Evans 1992). *Taungya* is a silvicultural practice of growing food crops in conjunction with trees while the trees are young, this practice was proposed in Burma (Myanmar) in the 1830's to arrest the damaging effects of shifting cultivation on forested areas (Evans 1992). *Taungya* was actively implemented in Burma after 1850 (MacGillivray 1990) and by 1900, about 8,000 ha of teak were established there using this system (Wint 1978). *Taungya* is intended to satisfy both food production and a forest crop. It is usually carried out for the first two or three years in the life of a tree crop before canopy closure, and is intended to provide cover to protect the soil from erosion and other likely soil hazards that might occur due to soil exposure while the trees are young.

Taungya was first introduced into Ghana in 1928 (Amanor 1996) in order to solve land shortage problems experienced by farmers living near forest reserves. *Taungya* was also introduced to enable the forestry Department to gain cheap labor for plantation development (Brookman-Amissah 1978). *Taungya* in Ghana involved replacement of poorly stocked natural forests by even aged plantations. The Forestry Department leased land to peasant farmers who cleared and, usually burnt the debris after clearing the site. The farmer or *taungya* group was assisted by the Forestry Department in planting the trees. The Farmer or *taungya* group then tended and protected both food crops (*e.g.*, maize, cocoyam, groundnuts, *etc.*) and planted tree seedlings. Compatible crops were selected so that they would not overtop the tree species. Also, animals were prevented from foraging in the planted areas. The practice was continued until tree canopy covered the ground and suppressed crop growth. The farmer or *taungya* group was then re-allocated land to start a new *taungya* and the trees allowed to grow. Allocation of another *taungya* depended on the success of the previous one. The farmer benefited from the harvested crops and the trees belonged to the Forestry Department. A search for a strategy to encourage farmers to conserve and preserve elements of the forest has currently led to the introduction of incentives and legal reforms that give farmers the right in the trees they plant and tend (Amanor 1996).

Evans (1992) summarized reasons for plantation establishment into negative and positive factors. Negative factors included,

1) past and continuous destruction of natural forest,
2) problems of access to existing forest,
3) unsatisfactory natural regeneration, and

4) lack of management.

Positive factors included,

1) land availability,
2) high productivity of plantations,
3) industrial plantations as a tool of development,
4) social and environmental forest values, and
5) plantations act as sinks for carbon.

2.3. EFFECT OF PLANTATIONS AND NATURAL FOREST ON SOIL PROPERTIES

There remains considerable debate among the following statements that have been made with respect to plantation versus native forest effects on the ecosystem:

1) Organic matter content, cation exchange capacity (CEC) and exchangeable cations are higher in soils under natural forest and miscellaneous plantations than in soils under plantations established as monocultures (Prasad *et al.* 1985, Singh and Totey 1985, Mongia and Bandyopadhyay 1992).
2) Plantation forestry results in soil compaction and nutrient immobilization in the standing biomass (Aborisade and Aweto 1990, George and Varghese 1992).

Michelsen *et al.* (1993) compared the effects of natural forest with the effects of two exotic tree species (*Cupressus lusitanica* and *Eucalyptus globulus*), and the indigenous species *Juniperus procera* in Ethiopia on soil fertility, shoot and root growth, nutrient utilization and mycorrhizal colonization. Soils under the two exotic tree plantations had lower OM and nutrient contents than soils under *J. procera* and soils under natural forest. These results were similarly found by Lisanework and Michelsen (1993). Singh and Totey (1985) observed higher cation exchange capacities, exchangeable cations and OM in soil under mixed plantations than under monocultural ones. Soils were more compacted under plantations than under natural forest (Laurie and Griffith 1992, Mongia and Bandyopadhyay 1992).

2.3.1. Nutrient Allocation In Teak

Aborisade and Aweto (1990) and Chava and Pandit (1989) attributed poor nutrient status under teak plantations to nutrient immobilization in the fast growing exotic. This was similarly reported by Nwoboshi (1984). The greatest demand in a teak plantation age series in Nigeria for soil nutrients, were for soil P, N and Ca. Proportions of these nutrients that reached the foliage decreased with age. In contrast, proportions of P, N and Ca cycled to trunk and branches increased with age. Available P concentration showed a significant decline with plantation age but K showed little variation (Marquez *et al.* 1993). Calcium, Mg, pH and CEC were significantly higher in older plantations than younger plantations (Nath *et al.* 1988, Marquez *et al.* 1993). Large amounts of Ca were stored in the bark of teak (Nwoboshi 1984, Zech and Drechsel 1991) and smaller amounts in the bark-free bole. Calcium was found to range from (400-427 kg ha^{-1}) in the bark and smaller amounts in the bark-free bole, about 166 kg ha^{-1} (Kaul *et al.* 1979), therefore, tree harvesting had the potential for site nutrient depletion. Hase and Foelster (1983) found that the removal of teak wood resulted in losses of Ca (220-3070 kg ha^{-1}), in rotations of 50 years, and decreased soil pH and biological activity. In such cases, these studies were in general agreement with the findings of (McColl and Powers 1984, Aborisade and Aweto 1990, George and Varghese 1992). It has been recommended by all of these authors that the bark, foliage, small twigs and branches be left in the plantation during teak harvest.

2.3.2. Changes In Soil Properties Under Pure Teak Plantations

Varying opinions have been expressed regarding the possibility that soils under pure teak plantations undergo a gradual deterioration with a consequent degradation in the quality of teak and the environment. In plantations at Nilambur, India, Brandis (1921) pointed out that it was difficult to foresee the risk of deterioration to which pure teak forest may be exposed. Similarly, Griffith (1937), and Manning (1941) asserted that apart from secondary influences such as erosion, fire and heavy grazing, evidence for deterioration of soil under teak plantation was sometimes lacking, but believed that changes in soil properties were likely. Laurie and Griffith (1942) latter discovered that surface soil under teak plantations sometimes hardened, aeration decreased, and soil erosion increased. However, under other pure teak plantations in India, these authors had no reason to suspect wide scale soil deterioration under teak plantations. 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.

In other recent studies by (Bell 1973, Chunkao *et al.* 1976, Karunakaran 1984, Kushalappa *et al.* 1987), soil erosion and sediment yields were higher under teak plantation than other cover types due to heavy grazing pressures and repeated fires.

In Nigeria, Totey *et al.* (1986) compared the changes of soil physico-chemical properties under three different vegetations, namely: 1) miscellaneous (mixed wood) forest; 2) eucalyptus plantation; and 3) teak plantation. Totey *et al.* (1986) reported that weathering processes, ratio of clay to non-clay fractions, OM, CEC, and exchangeable Ca and Mg were higher under teak cover than Eucalyptus and miscellaneous forest. These authors attributed the higher CEC under teak to higher OM. Higher available Ca and Mg was attributed to incorporation and decomposition of teak leaf litter high in Ca and Mg (Upadhya 1955). Overall, these soil chemical changes were similar to those reported by (Choubey *et al.* 1987, Bhoumik and Totey 1990, George and Varghese 1990, Krishna Kumar *et al.* 1991).

Teak planted at higher densities have been found to have higher OM, exchangeable Ca and CEC (Singh *et al.* 1986, 1988).

Mongia and Bandyopadhyay (1992), monitoring changes occurring in tropical forest soils under high value plantation crops, found that soil Db increased under teak but not under virgin forest. They attributed this to loss of OM under teak. Furthermore, they found that the natural forest had higher exchange base status than teak. This they attributed to efficient recycling of Ca and Mg under teak and to higher demand for these nutrients by teak and less for natural forest. The decline in OM content under teak more affected the cycling of N and P and resulted in the reduction of N and P (Mongia and Bandyopathyay 1992). These findings were consistent with the claims of Laurie and Griffith (1942), and Aborisade and Aweto (1990).

Teak harvest in Venezuela has been found to result in considerable loss of soil Ca through biomass removal (Hase and Foelster 1983), and loss of N, S, and K through leaching and erosion (McColl and Powers 1984, Balagopalan 1987). Furthermore, it is generally feared that large teak plantations could lead to soil deterioration through increased soil erosion (Kadambi 1972, White 1991), soil compaction and consequent decrease in aeration (Laurie and Griffith 1942, Aborisade and Aweto 1990, Mongia and Bandyopadhyay 1992), and loss of indigenous species in the long term (Awuah 1995). However, studies on the change in soil properties caused by pure plantations of long rotation crops are few (Yadav and Sharma 1968, Jose and Koshy 1972).

2.4. CONSEQUENCES OF FOREST MANAGEMENT ON SOIL PROPERTIES

Kimmins (1977) listed six questions, reproduced below that should be considered when evaluating the consequences of timber harvesting on future site productivity:

1) What proportions of the site nutrient (both available and total soil nutrient levels) capital is removed as harvested materials?
2) How rapidly does the remaining nutrient capital cycle at the site? How available are the nutrients to plants?

3) How rapidly are nutrient losses replenished and by what mechanisms? Are these mechanisms affected by the harvesting treatment ?
5) What is the magnitude of other harvest- induced losses of nutrients?
6) How frequently will harvest-induced nutrient losses occur ? What is the rotation length?

In the context of Kimmins' questions, an attempt was made to establish the relative sizes and differences of nutrient capital in soils under teak plantations and adjacent native logged forest ecosystems.

2.4.1. Harvesting Effects on Physico-chemical Properties of Soil

Forest management practices from site preparation to stand tending, and to final harvest affect and alter physical, chemical, hydrological and biological properties of the site (McColl and Powers 1984). Harvesting managed forest land usually means that nutrients tied up in wood will be removed periodically (McColl and Powers 1984, Nwoboshi 1984, Zech and Drechsel 1991). Conventionally, only the trunk is removed leaving branches and leaves. However, in more intensive management, trunks, branches and foliage might be removed. This might result in substantive changes in physico-chemical site properties and processes.

Harvesting also might result in: 1) soil compaction from the movement of logs and heavy machinery over a site, 2) decreased aeration due to compaction (Kimmins 1987), and 3) loss of nutrients through leaching (McColl and Powers 1984, Kimmins 1987, Eden *et al.* 1991).

The effects of nutrient removal on ecosystem nutrient budgets will depend on the type and frequency of harvesting, intensity of product removal, characteristics of site and stand, tree species, and rotation length (McColl and Powers 1984, Nwoboshi 1984, Kimmins 1987).

Stone (1973) estimated that N losses through harvesting stemwood and bark were 50 kg ha^{-1} , P losses were 10 - 30 kg ha^{-1}, and Ca losses were 100 - 1,000 kg ha^{-1}. These, he anticipates could be multiplied by two to three times when conventional above ground tree harvesting techniques were replaced by more intensive harvesting systems. Similarly, Nwoboshi (1984) estimated that intensive harvesting of a 15-year old teak plantation in Nigeria resulted in the loss of more than 50 to 60 percent of the total nutrients taken up from the soil during the rotation.

Tropical forest soils are thought to be more vulnerable to nutrient loss through harvest compared with temperate soils, in part because greater proportions of nutrients are immobilized in standing biomass and because storage is low in the forest floor (McColl and Powers 1984, Chava *et al.* 1989, Michelsen *et al.* 1993). Tropical sites are poorly buffered against fertility loss due to the absence of forest floor and its associated nutrient pool (McColl and Powers 1984). Therefore, proportionally more nutrients may be removed from a site through harvesting in the tropics than in the temperate zone (McColl and Powers 1984, Chava *et al.* 1989, Michelsen *et al.* 1993). Consequently, site quality reductions could be greatest in the tropics (Chava *et al.* 1989, Michelsen *et al.* 1993).

Rotation length is also an important factor that determines nutrient removal. Generally, short rotations tend to remove nutrients at a faster rate than long rotations (Kimmins 1987). Shortened rotations mean a greater proportion of the rotation length is spent in site preparation. Forest floor disturbance is greatest during the period before full site occupancy and nutrient losses may be higher Webber (1978). It has been postulated that more nutrients will be removed in several short rotations than in an equivalent harvest in a longer rotation (Hase and Foelster 1983 , McColl and Powers 1984). In addition, longer rotations will allow the site a greater recovery time than do shorter rotations. In Australia, Mitchell (1970) compared expected loss of N and P from two 20-year rotation with five thinnings from *Pinus radiata* stands on podzolized sands. Estimated losses for N was 284 kg ha^{-1} and for P was 24 kg ha^{-1} for one 40-year rotation compared to 336 kg ha^{-1} for N and 28 kg ha^{-1} for P for the two 20-year rotation, The two 20-year rotations represented 18 % more N and P loss than the single 40-year rotation.

Tree species vary greatly with respect to growth rate, nutrient content, nutrient requirements and distribution of nutrients among the various tree components (Freedman 1981, Singh and Totey 1985, Michelsen *et al.* 1993). Harvesting a deciduous forest before leaf fall generally, removes more nutrients than harvesting conifers of similar biomass (McColl and Powers 1984). Harvesting species having high foliar nutrient concentration will result in large nutrient removals than harvesting species having lower foliar nutrient concentrations (Kimmins 1987). For example, hardwood species generally have higher nutrient concentrations in their foliar tissues, than do conifers. Therefore, greater losses of nutrients such as N, K and Ca could be expected from the harvesting of a hardwood stand than occurs from harvesting a conifer stand in the same season Maliondo (1989).

Furthermore, fast growing, short rotation tree species produce more biomass, thus are more demanding on a site compared with slow growing species. Harvesting such species will result in more nutrient losses than harvesting slow growing tree species. For Example, McColl and Powers (1984) compared nutrient losses of fast growing short rotation *Pinus radiata* to less demanding native Eucalyptus hardwood species in Australia. They discovered that, harvesting a 40-year rotation *Pinus radiata* removed 4.5 times more P than harvesting a 57-year rotation of *Eucalyptus delegalensis*.

Fire as a Management Tool

Fire is sometimes an important component for the regeneration of teak within its natural range. Fire can eliminate competing vegetation but may also weaken and cause adverse effects on soils and on teak growth.

Fire is sometimes used to control bamboo in the natural range of teak, thus enhancing the natural regeneration of teak. In the drier forest, fire may kill young trees and may damage large trees. Much damage to young teak plantations was caused by fire in Nigeria (Troup 1921). Furthermore, fire also accelerates erosion under teak (White 1991) by removing undergrowth and protective litter layers. 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 forest of Kulamav, Kerela, India and concluded that fire had no effect on soil texture.

2.4.2. Site Preparation

According to McColl and Powers (1984), site preparation which can be accomplished by mechanical manipulation of soil surface and/or prescribed burning carries greater potential than any other single management practice for causing lasting changes in soil- tree relations. Mechanical site preparation can lead to nutrient loss both through increased erosion and leaching to ground water. McColl and Powers (1984) observed that foliar concentration of N and B, and surface soil N_t, and exchangeable Mg were lowered as a result of the loss of 26 cm of topsoil by mechanical site preparation in a *Pinus radiata* plantation.

Furthermore, site preparation can result in soil compaction. Compacted soils have low pore volumes and higher bulk densities. Thus, soil aeration, water infiltration, water retention, and saturated hydraulic conductivity are decreased while soil strength increased (McColl and Powers 1984, Kimmins 1987). Consequences include increased surface water runoff resulting in increased soil erosion, thus reduction of site productivity occurs. Also, this results in reduced root penetration, and less available soil moisture and oxygen.

Soils low in OM are more vulnerable to compaction and increased bulk densities (McColl and Powers 1984).

According to Neal *et al.* (1965), Tarrant (1956), and Krause (1991), the use of low-intensity prescribed burning for site preparation often raises the availability of P and N. The concentration of exchangeable K may increase in the surface, but such change would likely be of a temporary nature due to the mobility of K. During burning, N and S are oxidized rapidly once temperatures reach 200° C, and may be lost as volatiles or fly ash, increasing proportionally with burning intensity.

2.5. MODELING BULK DENSITY

Bulk density (Db) is an important soil physical property, used to estimate the magnitude of the total nutrient pool stored in the forest soils and is critical for nutrient budget and sustainability studies. Db is an indirect measure of the total pore space in the soil and is affected primarily by the proportions of primary mineral particles (sand, silt, and clay; texture) and the aggregation (structure) of the primary particles, and OM.

Db expressed as g cm^{-3}, is the weight of an oven-dry (Wo) sample of undisturbed soil per unit or 'bulk' volume. The soil sample is dried at 105°C.

Two mathematical expressions of Db are:

$$Db = \frac{Ws \ (g)}{Vs + Vw + Va \ (cm^3)} \qquad [1]$$

$$Db = \frac{Ws \ (g)}{Vb \ (cm^3)} \qquad [2]$$

where Ws = weight of soil (g), Vs = volume of soil (cm^3), Vw = volume of water (cm^3), Va = volume of air (cm^3), and Vb = bulk volume (cm^3).

Bulk volume includes volume of soil, volume of water, and volume of air:

$$Vb = Vs + Vw + Va \qquad [3]$$

Usually, if the aggregation of a soil leads to a granular structure, the total pore space will be increased, and the weight per unit volume or Db of the soil will decrease (Brady 1990). The Db of fine textured mineral soils may range from about 1.0 to 1.3 g cm^{-3} and that of sandy soils from about 1.3 to 1.7 g cm^{-3}(Foth 1990). The Db of organic soils is usually much less than that of mineral soils and may be lower than 0.4 g cm^{-3} (Fonteno 1996). Bulk density alone is not enough to indicate a soil's suitability to support plants. Soils of different Db's, because of different textures, may be equally good for plants (Foth 1990).

As an index of soil compaction, Db has been found to correlate negatively with root density (Strong and La Roi 1985, Gale and Grigal 1987), and tree growth (Hamilton and Krause 1985, Froelich *et al.* 1986). Bulk density is often strongly correlated with soil OM content and soil texture (Alexander 1980, Grigal *et al.* 1989, Huntington *et al.* 1989, Manrique and Jones 1991). Differences in Db among soils in the United states, Hawaii, and Puerto Rico have been found to be primarily , due to differences in particle size distribution (Manrique and Jones 1991). Bulk density almost invariably increases with soil depth (Manrique and Jones 1991). This is partially attributed to higher OM in the surface layer and to tillage practices that causes relatively loose structure in the surface layer and compaction in the subsoil (Manrique and Jones 1991, Tamminen and Starr 1994).

The determination of Db requires taking several representative volumetric soil samples of mineral soils, which is often labour-intensive, time consuming, and difficult, particularly for stony soils. There is, therefore, a considerable need for the development of alternative predictive models of Db as a function of a set of soil physico-chemical properties that are easily measurable.

Several procedures have been developed to predict Db based on soil textural components and OM. Shaffer (1988) predicted Db as a function of clay content for soils of Minnesota. Huntington *et al.* (1989) predicted Db for California soils as a function of $\sqrt{(C\%)}$ or Log C%. Tamminen and Starr (1994) predicted Db for Finnish soils using $\sqrt{OM}$. Alexander (1980) has also used the square root transformation of OM or carbon content to explain soil Db of mineral soils. Van Wambeke (1974) predicted Db for Oxisols based on sand fraction. Jones (1983) used silt and clay contents to predict Db for soils with fragipans.

Alexander (1980) and Grigal *et al.* (1989) observed that the relationship between Db and OM was more linear in the study of Tamminen and Starr (1994) in Finland than reported in other studies, and was attributed to the narrow range of OM in the Finnish study (Tamminen and Starr 1994). Tamminen and Starr (1994) further observed that clay content $\geq 7\%$ significantly improved prediction of Db in Finland.

Most forest soils in Ghana are stony, and it is difficult to estimate their bulk densities. Also, quantitative data on Db of forest soils in Ghana is lacking. My objective is to present Db values and regression models of bulk density as a function of easily measured soil physico-chemical properties

3.0 MATERIALS AND METHODS

3.1. BRIEF DESCRIPTION OF THE NATURAL VEGETATION AND SOILS OF GHANA

Ghana is situated in West Africa between approximately 4°45' N and 11°10' N, and 1°12' E and 3°15' W. About one-third of the country is less than 150 metres above sea level, and half is between 150 metres and 300 metres. Most of the remaining area lies between 300 and 600 metres in altitude. Much of the country is gently undulating with some marked escarpments, but no great heights (Prah 1994).

The natural vegetation (Figure 4) of Ghana is closely related to climate and is classified by Taylor (1960) into the following.

1) Savannah
    - i) Guinea Savannah-Woodland
    - ii) Sudan Savannah
2) Tropical High Forest
    - i) Tropical Forest
    - ii) Tropical Rain forest
3) Coastal Scrub and Grassland, and
4) Maritime (strand and mangrove swamp)

Of concern to this study are the Guinea Savannah-Woodland, and the Tropical High Forest zones.

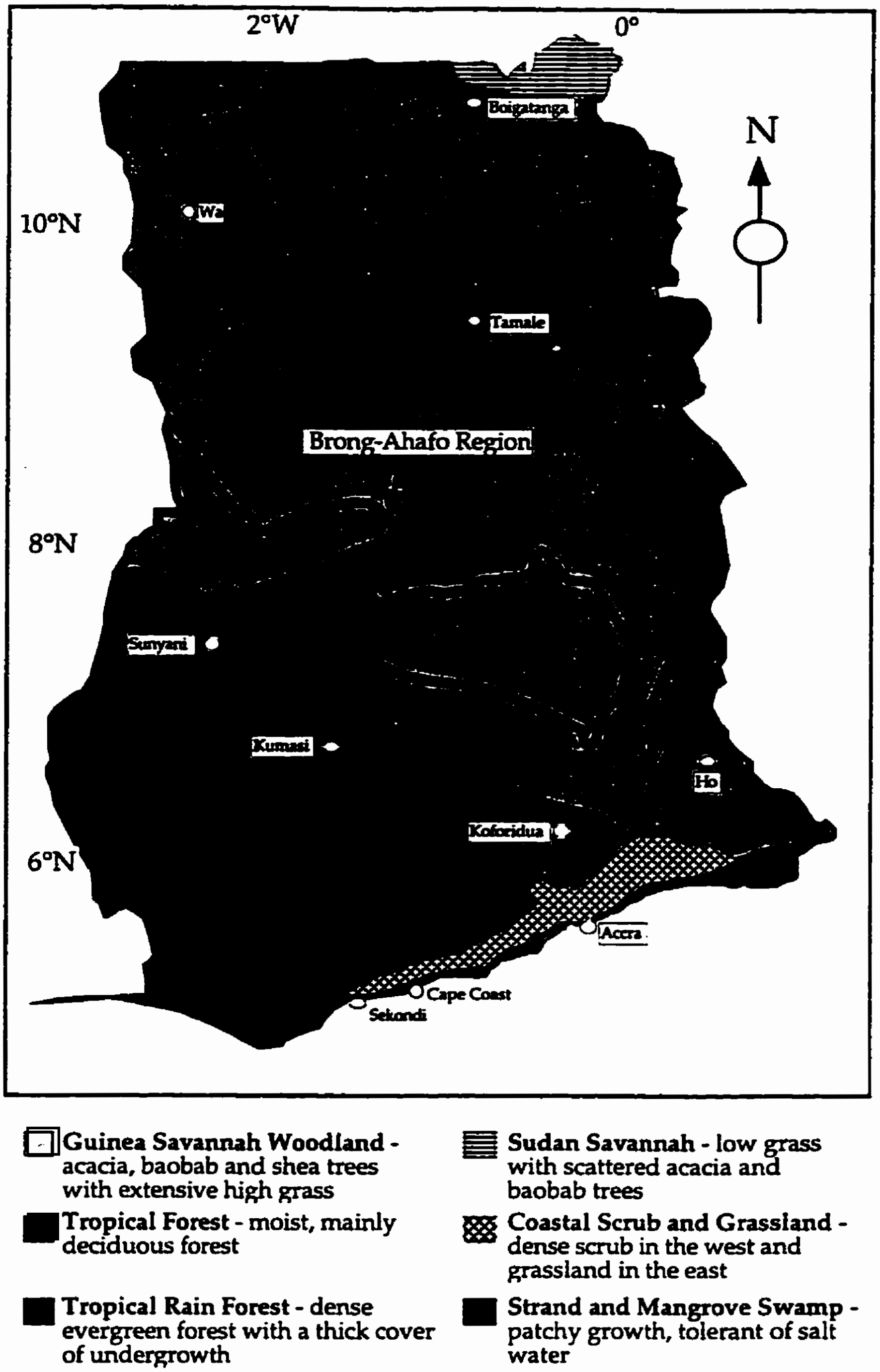

Figure 4. Natural vegetation of Ghana.

The major rock types in Ghana are similar in age and in mineral composition and are made up of considerable amounts of quartz and granite (Boateng 1966). Due to the fundamental similarities in geology, it is largely climate and vegetation that determine soil differences (Boateng 1966). Based on climate and vegetation, soils of Ghana are broadly classified into nine broad soil types (Figure 5).

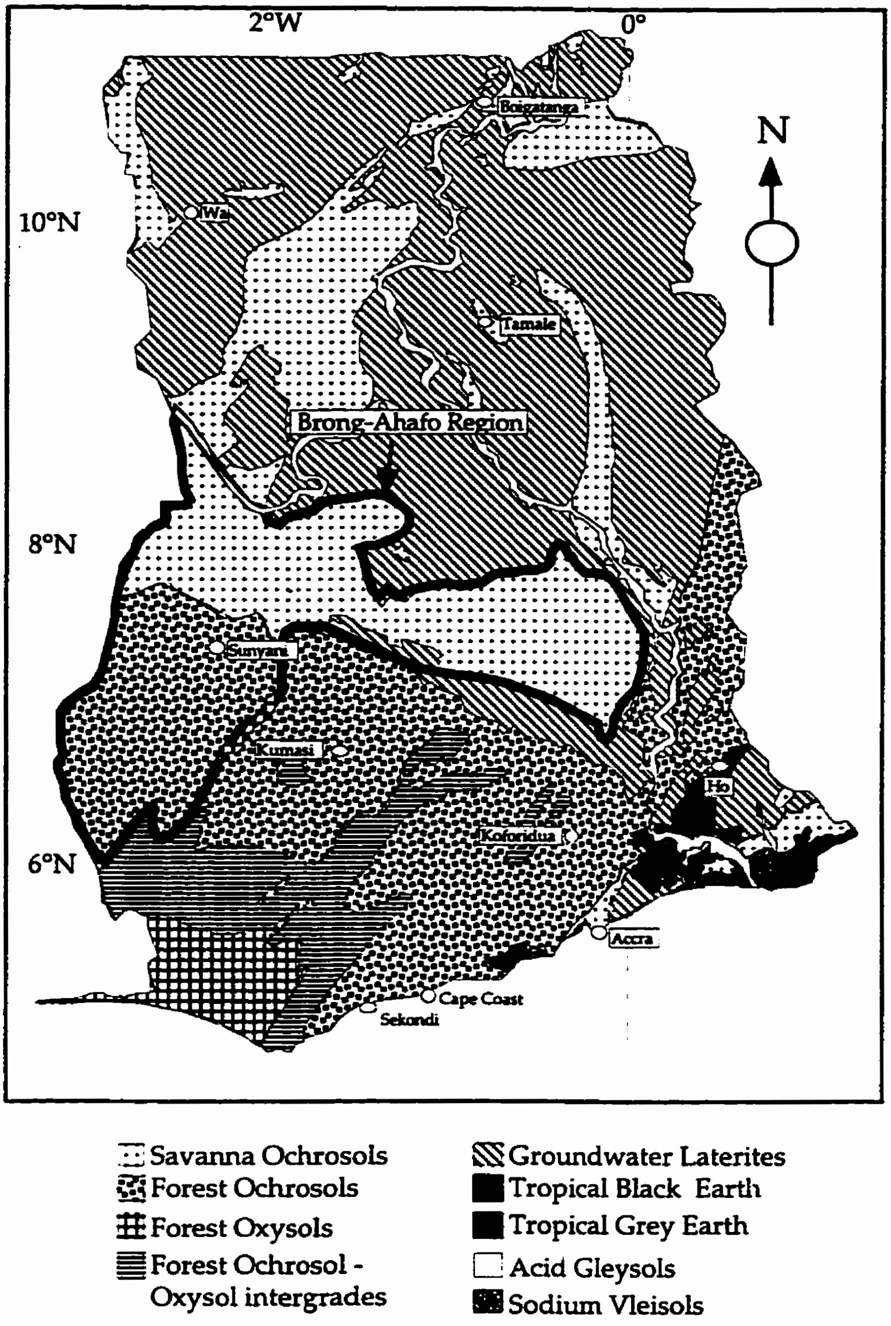

Figure 5. Major Soil types of Ghana.

The soils in Ghana and in most other African countries may obtain N from N-fixing plants and by lighting. However, these soils depend on plant humus for most of their plant nutrients (Boateng 1966). This is due to the fact that, most of the rocks are composed of materials that have undergone prolonged weathering and have lost most of their potential nutrients to either groundwater or to plant biomass (Boateng 1966, Young 1976).

3.1.1. Savanna Woodland

Climate

The Savanna-Woodland is located north of the high forest. Most of this area lies within the one peak rainfall zone where the peak is in August-September. The precipitation is seldom less than 1000 mm per annum and may reach 1270 mm. The area experiences an intense dry season from December to April. Six years mean rainfall and temperature of the studied locations is illustrated in Figure 6. Kintampo is located closer to The High Forest zone, as such experiences a bimodal rainfall pattern as The High Forest.

Vegetation

The vegetation of the savanna woodland is typically composed of short-statured, many branched trees, often less than 15 metres high. Trees are widely spaced with open canopy. The most common tree species include, *Gmelina arborea, Anogeissus species, Daniela oliveri, Triplochiton scleroxylon* and *Borasus* palm. The ground flora is composed of grasses such as *Emperata cylindrica, Andropogon gayanus, Panicum maximum* and *Cynedon ductilon.*

Soils

The study was conducted on savanna *Ochrosols*. The savanna Ochrosols are found on the Voltaian sandstones and are well-drained and generally red to reddish brown in colour (Boateng 1966). The soils are underlain by ancient rocks with considerable quartzite, granite, and gneisses over large areas (Boateng 1966). The savanna Ochrosols are referred to as Haplic Acrisol (F.A.O. UNESCO 1988), Figure 5. These soils tend to be inherently deficient in P and N. Despite this, these soils are able to support excellent plant growth in the Northern savanna zone (Boateng 1966).

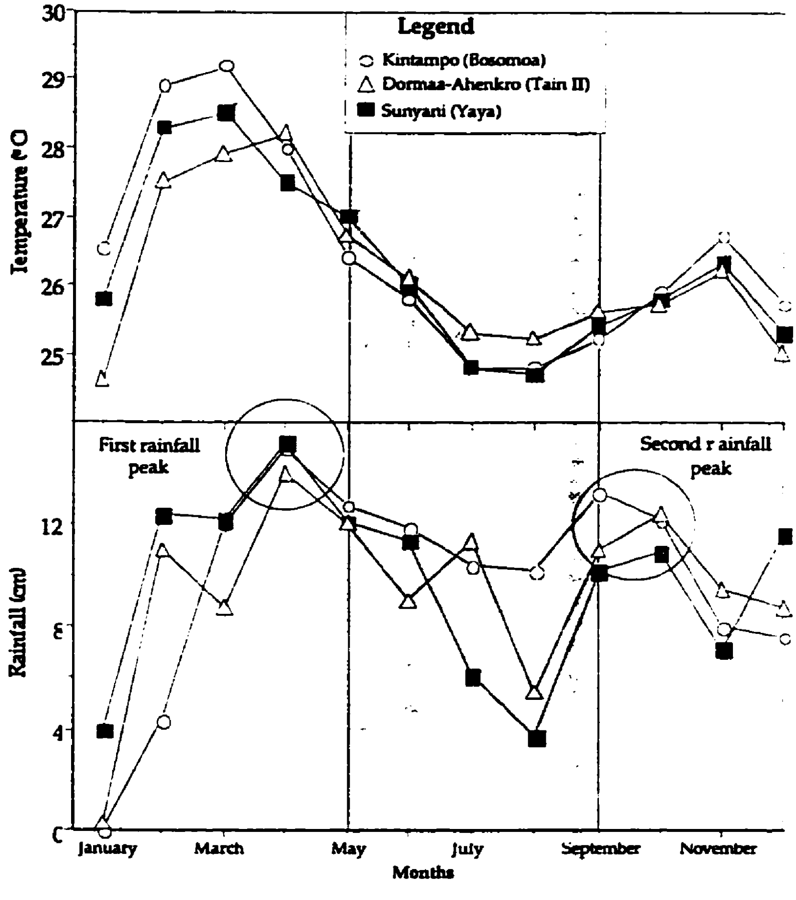

Figure 6. Mean monthly Temperature (°C) and Rainfall (cm) of studied locations (Data obtained from Ghana Meteorological Services Station at Sunyani, 1990-1996).

3.1.2. High Forest Zone

Climate

The High Forest zone experiences a tropical and humid climate having high temperatures. The average annual temperature is between 20°C and 26°C with little seasonal variation. The High Forest experiences a bimodal rainfall per annum (1,500 mm - 2,000 mm). The major season rains start from mid March to the end of July. The minor seasons rains start in September to mid November. Generally, the dry season is from December to March. Six years mean rainfall and temperature of the study locations, Sunyani, and Dormaa-Ahenkro are illustrated in Figure 6.

Vegetation

The High Forest zone is divided into four broad ecological types- the Wet Evergreen (WE), the Moist Evergreen(ME), the Moist Semi-deciduous(MSD) and dry Semi-deciduous (DSD)(Hall and Swaine, 1981). Floristically, these are synonymous with the *Cynometra-Lophira-Tarrietia*, *Lophira-Triplochiton*, *Celtis-Triplochiton* and *Antiaris-Chlorophora* associations (Taylor 1960).

The High forest is a heterogeneous collection of uneven-aged trees, multi-layered with three incompletely defined strata (Taylor 1960). Emergent trees may reach a height up to 60 metres. Some of the emergents include, *Triplochiton scleroxylon*, *Ceiba pentandra*, *Melicia excelsa*, *Terminalia superba*, *Antiaris africana*, and *Pycnanthus angolensis*. Ghana's most valuable timber species are found in this vegetation zone. Ground flora is sparse. Entwined throughout the stands are thick stemmed lianas and creepers, and abundance of epiphytes.

Soils

The soils are underlain by ancient rocks with considerable quartzite, granite, and gneisses (Boateng 1966). The soils are rich in humus and worm casts that give the A horizon it's characteristic dark brown colour. Below is ironstone concretions that give the soil a reddish brown colour (Boateng 1966).

The soils are *zonal* (USDA 1938), and belong to the great soil group of Latosols (Webster and Wilson 1966). Charter (1957) divided the widespread Latosols of the zone into Ochrosols and Oxysols .

The ochrosols are usually red or reddish brown on summits and upper slopes of hills, orange-brown or brown on middle slopes and yellow brown on lower slopes. The Ochrosols are less leached, better drained, fertile and are the most important soils in Ghana from the agricultural point of view (Boateng 1966). The forest Ochrosols are referred to as Haplic Ferralsols (F.A.O. UNESCO 1988) Figures 5 and 7.

The forest Oxysols are usually orange-brown to yellow-brown on hill summits and upper slopes. They are highly leached and more acid and have less humus than Ochrosols (Boateng 1966).

3.2. STUDY SITE LOCATIONS AND SURVEY PROCEDURE

The study was conducted in the Bosomoa Forest Reserve (Kintampo), the Tain II Forest Reserve (Dormaa-Ahenkro), and the Yaya Forest Reserve (Sunyani) in the Brong-Ahafo region of Ghana (Figure 7). Henceforth, these locations will be referred to as Bosomoa, Tain II and Yaya, respectively. The three study locations lie between 7°10' N and 8°15' N latitude and 1°30' W and 3°W longitude. Bosomoa is located in the Savanna

Woodland vegetation zone. Tain II, and Yaya are located in the Moist Semi-deciduous forest of the High Forest zone (Figure 4).

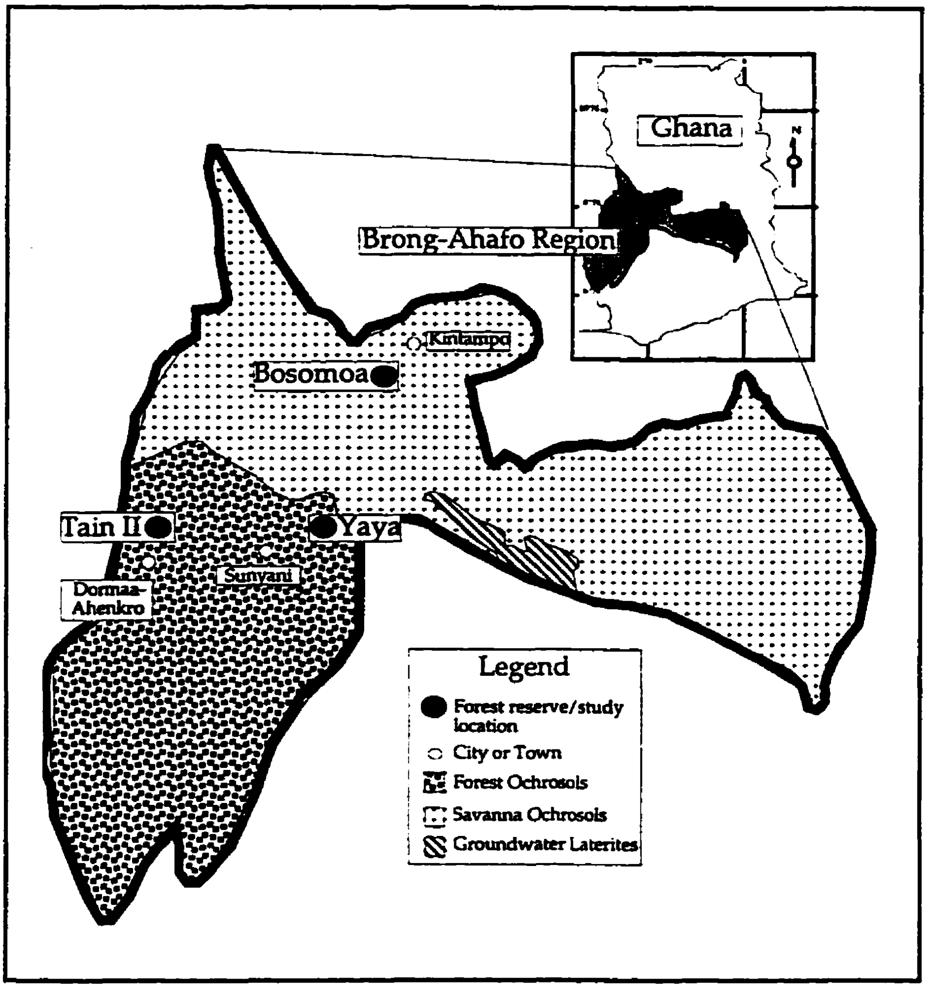

Figure 7. Study locations in the Brong-Ahafo Region of Ghana.

Exploratory site surveys using maps, plantation records (available from Regional Forestry offices in Ghana), and ground surveys were conducted at Bosomoa, Tain II and Yaya in May, 1996 to locate,

1) compartments with similar geology, topography, drainage, and teak plantations having similar ages and stocking, and
2) available adjacent logged forest having similar geology, topography, and drainage.

Adjacent logged forest was used as the basis for comparison with the teak plantations. Site pairs were chosen on the basis of perceived similarities in geology, topography, and drainage. Before teak plantations were established, all site pairs for this study had been natural logged forest. The associated soil for all sites selected for this study were not considered degraded. According to District foresters, fire occurred in equal intensities in all pairs of teak/logged forest before and after teak establishment.

Areas of natural logged forest selected for teak establishment were prepared by clearing the land of remaining trees, burning with a low intensity fire and planting with teak and crops immediately after clearing (pers. comm. Ashadu, 1996 and Diabore, 1996). This ensured that soils at the sites were exposed for a minimal amount of time. Usually, teak canopy closure occurred within three years at these sites, thereby eliminating crop species. It is possible that this short period of soil exposure during the teak establishment may account for differences found in soil properties between teak and the natural logged forest for this study. Therefore, differences in soil properties are not to be solely associated with teak cover; differences in soil properties may be due to a combination of site preparation and the change to teak cover.

Although there was adequate numerical data available for the teak plantation assessment, the assessment of composition and stand structure similarities in the adjacent logged native forest was necessarily visual.

A total of 14 teak plantations/logged forest pairs and one unthinned teak plantation met the above criteria and were selected for the study. Details of the study areas are given in (Table 1 and Figure 7).

Table 1. Plantation characteristics of Bosomoa, Tain II and Yaya.

Location (vegetation/soils)	Forest Reserve (Series)		Compartment. No.	Plantation. age	Stems per ha
Kintampo (Savannah woodland/ Savannah Ochrosol)	Bosomoa		43	25	*
			67	29	*
			68	23	*
			83	25	*
			108	23	*
Dormaa-Ahenkro	Tain II	(Dwenewoho)	146	24	349
		(Dwenewoho)	147	27	295
(High forest/		(Namasua)	160	22	352
Forest Ochrosol)		(Nsuatre)	242	22	282
		(Nsuatre)	u242†	22	*
		(Ayakomaso)	280	25	242
		(Ayakomaso)	300	15	213
Sunyani (High forest/Forest Ochrosol)	Yaya		28	26	218
			33	24	262
			34	21	229

†u242 = unthinned compartment.
* = no information

The sample plots were restricted to Savanna Ochrosols at Kintampo (five pairs), forest Ochrosols at Dormaa-Ahenkro (six pairs), and forest Ochrosols at Sunyani (three pairs). Teak plantations were established on poorly stocked natural forest by clear felling in 1968 by the Forestry Department. Most of the teak plantations were introduced through the *Taungya* system. Portions of these plantations were used for this study.

Complete soil profile description sheets were completed for one large pit for each of the plots (APPENDIX XXIII) according to Agric. Can. (1987). Colours were assessed using a Munsell colour chart (Anon 1973). Samples were collected from the A (usually an 'Ah') and B ('Bt' for all Tain II and Yaya; B1 for Bosomoa) horizons from each of the four pits. Bulk density (Db) samples were collected from A and B horizons of only two of the four pits using a sharpened core sampler technique (Tamminen and Starr 1994). For the

Db samples, the face of the horizon was cleaned with a knife, and a sharpened cylinder of known volume (either a 50 cm^3 or 89.1 cm^3) was placed horizontally against the surface. Then a protective metal cap was placed against the cylinder and the cylinder was hammered gently into the soil (using a rubber mallet) until the soil projected about three mm out the cylinder end (Rowell 1994). The soil cylinder was then carefully dug free and soil extending beyond the open ends trimmed flush to the ends of the cylinder. The soil core was finally pushed into a plastic bag and transported to the laboratory for analysis.

3.3. SURVEY DESIGN AND SAMPLING INTENSITY

According to Crépin and Johnson (1993) as few as five to ten soil samples may be adequate for soil analyses on small sites (< 0.5 ha) that have been affected in a uniform way. However, large areas or those that vary more may need up to 25 samples. There is little gain in precision when sample numbers exceed 25 (Webster and Oliver 1990).

A simple random sample design (Figure 8) was executed at each of the study locations. Teak plantations and their adjacent natural forests were each represented by one randomly located 20m x 20m temporary sample plots (Vaheed Khan 1961, Sharma *et al.* 1983, Aborisade and Aweto 1990, Zech and Dreschsel 1991). Except for compartment 'u242' at Tain II, all of the teak plantations were selectively thinned.

In all the plots selected for the study, the following procedures were carried out:

1) 20m x 20m square plots were located approximately 100 m away from compartment boundaries.
2) Four 1m^3 soil horizons were randomly located and exposed on each plot (Figure 8), and their physical characteristics described. Two soil samples were taken at random from each pit from two genetic horizons (A and B) that represented approximately 80% of the rooting zone. Approximately 8 soil samples were collected per plot (Table 2). Eight soil samples per plot were presumed sufficient to provide statistically accurate estimates of soil physico-chemical properties, since plot sizes were small (0.04 ha).

3) The heights and diameter (dbh) of six dominant trees were measured on each teak plot using a Suunto clinometer and diameter tapes, respectively. Diameter (dbh) was also recorded for all trees contained in the plot. In the adjacent logged native forest, the tree species and understorey vegetation were recorded, but no height or diameter measurements were taken.

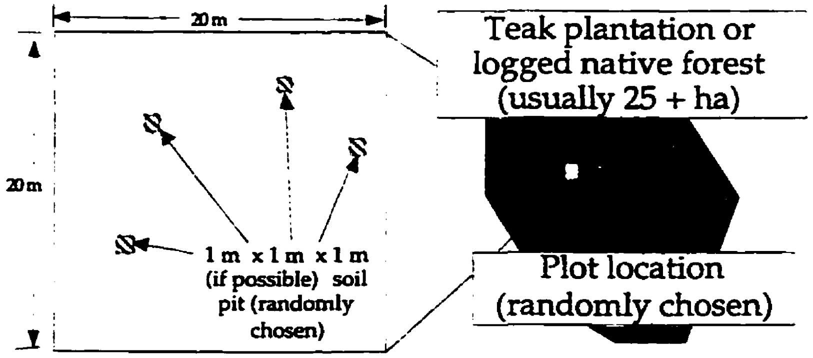

Figure 8. Plot layout for survey design.

Table 2. Sampling intensity for soil macro-nutrients by cover type.

Stand condition	No. of plots measured	No. of samples per plot	Total
Teak	15	8	120
Logged forest	14	8	112
Total	29	8	232

Table 3. Sampling intensity for soil Db and particle size by cover type.

Stand condition	No. of plots measured	No. of samples per plot	Total
Teak	15	4	60
Logged forest	14	4	56
Total	29	4	116

A total of (232 + 116 + 2) = **350** samples (Tables 2 and 3) were collected and analyzed for their physico-chemical properties following standard procedures (Aborisade and Aweto 1990, Zech and Dreschsel 1991). The two samples were extra samples taken from the logged forest of compartment 43 at Bosomoa.

3.4. LABORATORY ANALYSES

Particle size was estimated by the pipette method (IITA 1979). Bulk density was calculated (inclusive of the < 2 mm primary particles) using the methods of Tamminen and Starr (1994). Soil pH was determined potentiometrically, both in 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 (Bray and Kurtz 1945). Measurements were made at 885 nm on a Philips Pyre Unicam uv/visible spectrophotometer. Total nitrogen (total-N) was estimated by the Kjeldahl method (IITA 1979). Organic matter was estimated using loss on ignition (LOI) (Ball 1994). Exchangeable Ca, Mg, and K, and Al, Fe, Zn Mn and Cu 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 (1996).

Soil pH, Db, available P, total-N and texture were determined at the Savanna Agricultural Research Institute's soil chemistry laboratory at Nyankpala in Tamale, Ghana. The remaining analyses were done at the Forest Soils Laboratory at Lakehead University, Thunder Bay, Ontario.

3.5. DATA ANALYSES

SPSS version 6.1 and Microsoft Excel 5.0, were used for data analyses.

The following analytical procedures were employed:

1) plantation and natural forest variables were represented by plot means,
2) pooled mean values were used in comparing nutrient status of teak plantations and paired logged forest for Bosomoa, Tain II, and Yaya
3) one-way Analysis of variance was used to test for significant differences between teak plantation/logged forest pairs,
4) multiple regression techniques employing the backward method of variable selection was used to develop regression models for Db, using soil texture, pH, Vcf and soil OM as predictor variables.

3.5.1 Computation of Nutrient Contents

Total nutrient contents were estimated for Bosomoa, Tain II, and Yaya by:

$$\text{Total nutrient content (kg ha}^{-1}) = [\text{Nc (eq kg}^{-1}) \times \text{weight of soil (kg ha}^{-1})] \times \text{equivalent weight (kg eq}^{-1}) \quad [4]$$

$$\text{Nc (eq kg}^{-1}) = \text{Nc (eq / 100)} \times 10 \quad [5]$$

$$\text{Nc (eq / 100 g)} = \text{Nc meq / 100} \times \text{eq / 1000 meq} \quad [6]$$

$$\text{Weight of soil (kg ha}^{-1}) = [h - (h \times CF / 100)] \times Db \times \text{kg / 1000g} \times [A \times 10^8]\ \text{ha}^{-1} \quad [7]$$

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.

4.0 RESULTS

Data on the growth performance of teak by forest reserve and compartment number are summarized in Table 4.

Results of the soil micro-nutrient analyses are summarized in Appendices I, II and III. And computed nutrient contents by cover types are given in Appendices IV, V and VI.

An exploratory data analyses were carried out, using the individual teak plantation/ logged forest paired data (Appendices X, XI, XII, XIII, XIV, and XV). Teak plantations and their adjacent logged forest pairs were compared with respect to three measures of soil depth: the mean depth of the (A+B) horizons, the mean depth of the A horizons, and the mean depth of the B horizons (results not shown). All the three different comparisons led to similar conclusions.

However, the results of the comparisons were most meaningful and useful when the data were partitioned into the A and B horizons, respectively. Therefore, pooled means on which the results and discussion were centered were compared keeping the A and B horizons separate.

The 14 studied pairs of teak - logged forest were grouped by parent material and physical location.

Table 4. Site characteristics and growth of teak.

Location (vegetation/soils)	Forest Reserve (Series)	Compartment. number	Plantation. age (y)	Mean height (m)	Mean diameter at breast height (cm)
Kintampo (Savannah woodland/ Savannah Ochrosol)	Bosomoa	43	25	20.34	28.83
		67	29	24.69	34.50
		68	23	22.88	29.83
		83	25	23.68	34.17
		108	23	21.16	26.50
Dormaa-Ahenkro (High forest/ Forest Ochrosol)	Tain II (Dwenewoho)	146	24	25.97	31.13
	(Dwenewoho)	147	27	27.08	34.0
	(Namasua)	160	22	25.63	29.83
	(Nsuatre)	242	22	28.22	37.83
	(Nsuatre)	u242†	22	25.38	28.00
	(Ayakomaso)	280	25	29.76	32.33
	(Ayakomaso)	300	15	25.43	36.33
Sunyani (High forest/ Forest Ochrosol)	Yaya	28	26	22.95	35.83
		33	24	25.56	42.00
		34	21	25.68	32.50

†u242 = unthinned compartment.
mean height and diameter values are for 6-dominant trees in a plot.

4.1. COMPARISON OF SOIL POOLED MEANS UNDER TEAK/LOGGED FOREST PAIRS

The results of particle size analysis for Bosomoa, Tain II, and Yaya are given in Appendix XVI and are illustrated in Figure 9.

The texture analysis gave strong indications that the grouping of the 14 pairs of teak - native logged forest into the Bosomoa, Tain II, and Yaya was justified. Appendix XVI and Figure 9 show that there is a big difference in particle size distribution between locations. Figure 9 further shows that particle size distribution is similar under both cover types within location.

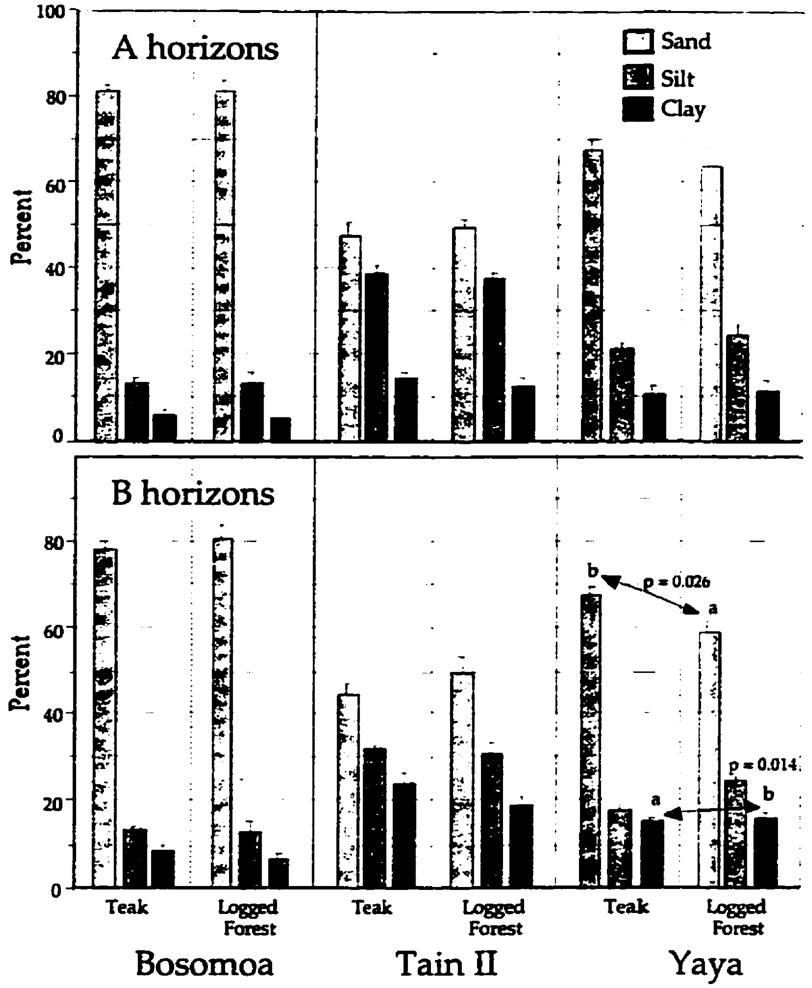

Figure 9. Particle size distribution of A and B horizons under teak and adjacent logged forest in the Bosomoa, Tain II and Yaya.

The results of macro -nutrient analysis for Bosomoa, Tain II, and Yaya are given in Appendix XVII, and are illustrated in Figure 10. Analysis of variance showed nutrients were generally higher in the A-horizons and decreased with depth across the three studied locations, Figure 10 and (Tables 5 to 10).

Bosomoa

Pooled means of physical properties of soil under teak/ logged forest pairs are presented for A and B horizons (Appendix XVI, and Figure 9). Soil textural class was loamy sand under both cover types. There were no significant differences in soil physical properties between the A or B-horizons under either cover types (Figure 9).

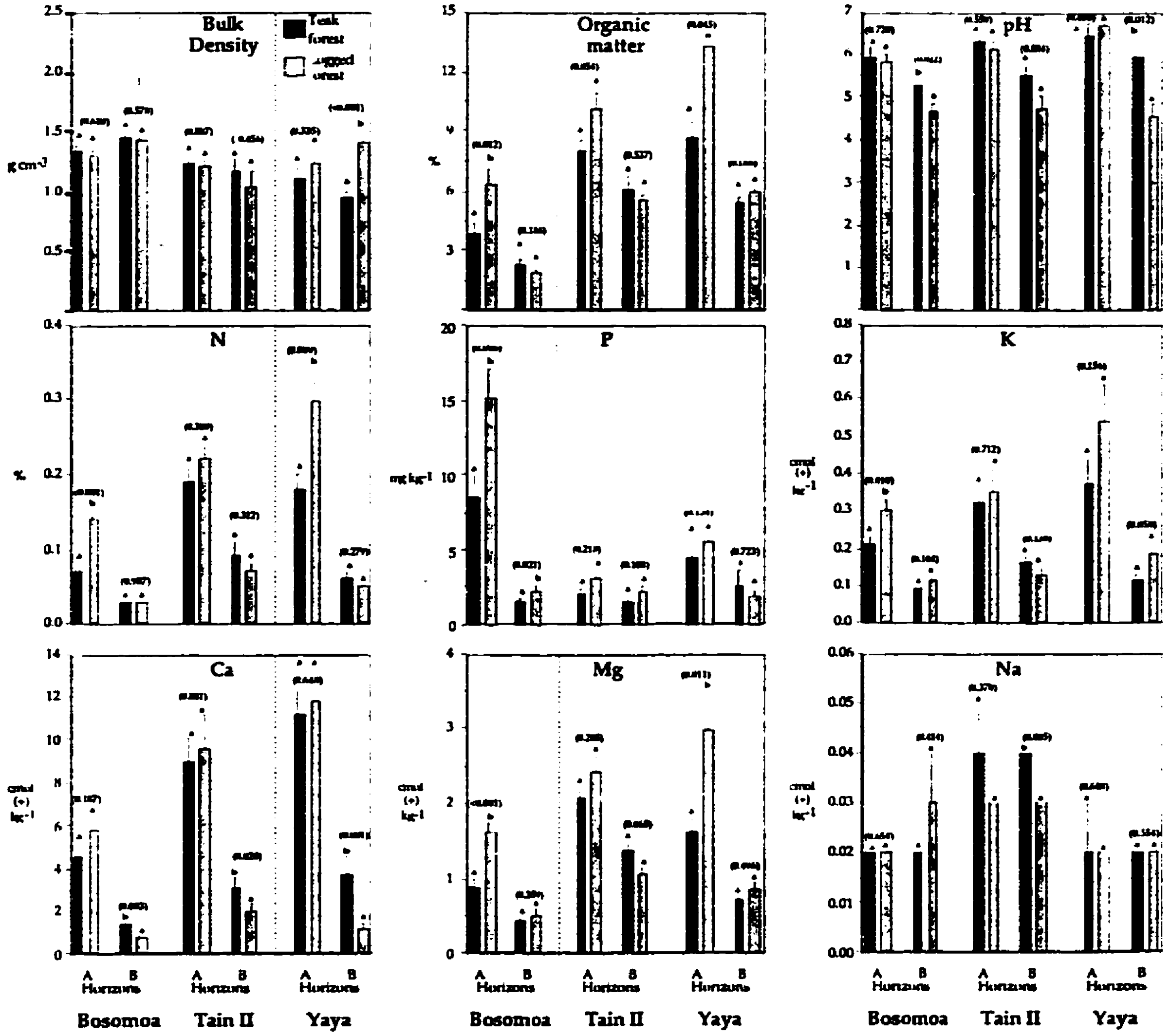

Figure 10. Bulk density, OM, pH, N, P, K, Ca, Mg, and Na distribution in A and B horizons under teak and adjacent logged forests in the Bosomoa, Tain II, and Yaya. For each data, differences in macro-nutrients between cover types within location are statistically significant when bars are marked with different letters.

Analysis of variance showed K was significantly higher ($P < 0.0101$) in the A-horizons under logged forest and decreased with depth under both ecosystems (Table 5). Similarly, Mg (Table 6), OM (Table 7), P (Table 8), and N (Table 9) were significantly higher ($P < 0.0002$, $p < 0.0120$, $p < 0.0062$ and $p < 0.0003$), respectively, in the A-horizons under logged forest and decreased with depth under both cover types (Figure 10).

Table 5. Average soil exchangeable K concentration: by location, horizon and cover type.

		Cover type	
		teak plantation	logged forest
Location	Horizon	K (cmol (+) kg^{-1})	
Bosomoa	A	0.21	0.30
	B	0.09	0.11
Tain II	A	0.32	0.35
	B	0.16	0.13
Yaya	A	0.37	0.54
	B	0.02	0.18

Table 6. Average soil exchangeable Mg concentration: by location, horizon and cover type.

		Cover type	
		teak plantation	logged forest
Location	Horizon	Mg (cmol (+) kg^{-1})	
Bosomoa	A	0.88	1.61
	B	0.43	0.52
Tain II	A	2.05	2.43
	B	1.37	1.06
Yaya	A	1.61	2.99
	B	0.72	0.84

Table 7. Average soil Om content: by location, horizon and cover type.

		Cover type	
		teak plantation	logged forest
Location	Horizon	OM (%)	
Bosomoa	A	3.78	6.31
	B	2.25	1.86
Tain II	A	8.00	10.09
	B	6.13	5.59
Yaya	A	8.66	13.18
	B	5.40	5.89

Table 8. Average soil available P concentration: by location, horizon and cover type.

		Cover type	
		teak plantation	logged forest
Location	Horizon	P (mg kg^{-1})	
Bosomoa	A	8.51	15.11
	B	1.57	2.28
Tain II	A	2.11	3.09
	B	1.55	2.17
Yaya	A	4.36	5.58
	B	2.59	1.83

Table 9. Average soil total N concentration: by location, horizon and cover type.

		Cover type	
		teak plantation	logged forest
Location	Horizon	N (%)	
Bosomoa	A	0.07	0.14
	B	0.03	0.03
Tain II	A	0.19	0.22
	B	0.09	0.07
Yaya	A	0.18	0.30
	B	0.06	0.05

Potassium (K) varied from 0.097 to 0.440 cmol (+) kg^{-1} with a mean and confidence interval (0.21±0.04) under teak plantations, and from 0.099 to 0.505 cmol (+) kg^{-1} (0.30 ±0.06) under logged forest (Table 5). Magnesium varied from 0.405 to 2.427 cmol (+) kg^{-1} (0.88±0.44) under teak plantations, and from 0.36 to 3.135 cmol (+) kg^{-1} (1.16±0.29) under logged forest (Table 6). Percent OM varied from 1.80 to 11.10 (3.78±1.13) under teak, and from 1.30 to 15.90 (6.31±1.75) under logged forest (Table 7). Total percent N ranged from 0.0283 to 0.2270 (0.07±0.02) under teak plantation, and from 0.047 to 0.2490 (0.14±0.02) under logged forest (Table 9).

In the B-horizons, Ca, and pH were higher ($p < 0.0026$, and $p < 0.0215$), respectively, under teak plantation (Table 10 and 11) and Figure 10. Phosphorus was higher ($p< 0.0214$) under logged forest (Table 8 and Figure 10). Calcium ranged from 0.32 to 4.12 cmol (+) kg^{-1} (1.43±0.42) under teak, and from 0.09 to 2.66 cmol (+) kg^{-1} (0.77±0.25) under logged forest. pH ranged from 4.62 to 6.42 (5.25±0.39) under teak plantations, and from 4.00 to 5.94 (4.66 ±0.38) under logged forest.

Table 10. Average soil exchangeable Ca concentration: by location, horizon and cover type.

		Cover type	
		teak plantation	logged forest
Location	Horizon	Ca (cmol (+) kg^{-1})	
Bosomoa	A	4.55	5.76
	B	1.43	0.77
Tain II	A	8.91	9.60
	B	3.14	1.96
Yaya	A	11.13	11.76
	B	3.69	1.13

Table 11. Average soil pH (in $CaCl_2$): by location, horizon and cover type.

		Cover type	
		teak plantation	logged forest
Location	Horizon	pH(in $CaCl_2$)	
Bosomoa	A	5.95	5.85
	B	5.25	4.66
Tain II	A	6.29	6.12
	B	5.49	4.76
Yaya	A	6.47	6.67
	B	5.98	4.53

Tain II

Analysis of variance showed that there were no significant differences in weighted means of soil physical and chemical properties under teak/logged forest pairs when the A-horizons were compared (Figure 9).

While physical properties remained similar under both cover types in the B-horizon (Figure 9), chemical properties differed. Calcium and Na were higher ($p < 0.0202$ and $p <$

0.0052), respectively, under teak plantation (Tables 10 and 12) and (Figure 10). Calcium ranged from 0.46 to 11.45 cmol (+) kg^{-1} (3.14 ±0.93) under teak, and from 0.31 to 7.10 cmol (+) kg^{-1} (1.96 ±0.72) under logged forest (Table 10). Sodium varied from 0.009 to 0.98 cmol (+) kg^{-1} (0.04 ±0.00) under teak plantations, and from 0.009 to 0.49 cmol (+) kg^{-1} (0.03 ±0.00) under logged forest (Table 12).

Table 12. Average Na concentration: by location, horizon and cover type.

		Cover type	
		teak plantation	logged forest
Location	Horizon	Na (cmol (+) kg^{-1})	
Bosomoa	A	0.02	0.02
	B	0.02	0.03
Tain II	A	0.04	0.03
	B	0.04	0.03
Yaya	A	0.02	0.02
	B	0.02	0.02

Yaya

Weighted means of physical soil properties in the A-horizons of teak/logged forest pairs were similar (Figure 9) and decreased with depth under both ecosystems. Pooled means of soil chemical properties indicated Mg (Table 6), N (Table 9) and OM (Table 7) were higher ($p < 0.0107$, $p < 0.0088$ and $p < 0.0153$), respectively, under logged forest (Figure 10). Magnesium ranged from 0.855 to 3.036 cmol (+) kg^{-1} (1.61±0.44) under teak, and from 1.413 to 6.411 cmol (+) kg^{-1} (2.99±1.08) under logged forest (Table 6). Nitrogen varied from 0.111 to 0.287 (0.18±0.04) under teak, and from 0.71 to 0.544 (0.30±0.09) under logged forest (Table 9). Percent OM ranged from 6.10 to 14.40 (8.66±1.65) under teak, and from 6.70 to 22.20 (13.18±3.41) under logged forest (Table 7).

In the B-horizons percent clay (Table 13) was significantly higher ($p<0.0143$) in soils under logged forest compared with soils under adjacent teak plantation. Also, Db's (Table 14) were higher ($p < 0.0007$) under logged forest (Figure 9). Percent Clay varied from 12.23 to 22.50 (17.78±2.80) under teak, and from 20.70 to 27.980 (24.27±3.60) under logged forest (Table 13). Bulk density ranged from 0.75 to 1.10 (0.94± 0.13) under teak plantations, and from 1.11 to 1.63 (1.40±0.21) under logged forest (Table 14). Percent sand was significantly higher ($P <0.0256$) under teak plantation (Figure 9), and ranged from 58.32 to 73.06 (67.15±5.76) under teak plantation, and from 52.13 to 64.26 (59.11±5.40) under logged forest.

Table 13. Average soil clay content: by location, horizon and cover type.

		Cover type	
		teak plantation	logged forest
Location	Horizon	Clay (%)	
Yaya	A	11	12
	B	18	24

Table 14. Average soil Db: by location, horizon and cover type.

		Cover type	
		teak plantation	logged forest
Location	Horizon	Db (g cm^{-3})	
Yaya	A	1.10	1.24
	B	0.94	1.40

Soil chemical properties were similar except for Ca and pH in the B-horizon. Calcium and pH were higher ($p< 0.0010$, $p< 0.0116$), respectively, under teak plantation (Tables 10 and 11) and (Figure 10).

Calcium ranged from 0.82 to 12.12 cmol (+) kg^{-1} (3.69±1.87) under teak, and from 0.25 to 3.89 cmol (+) kg^{-1} (1.13±0.66) under logged forest (Table 10). Soil pH ranged from 5.03 to 7.22 (5.98±1.00) under teak, and from 4.00 to 5.57 (4.53 ±0.72) under logged forest (Table 11).

4.2. COMPARISON OF MACRO- NUTRIENT CONTENTS OF SOIL UNDER TEAK/LOGGED FOREST PAIRS.

Total nutrients were computed for the A and B-horizons (Table 15, and 16), respectively, and (A+B)-horizon (Table 17), all illustrated in (Figure 11).

Table 15. Pooled total nutrients in A-horizons.

Location	Cover type	Mean horizon thickness (cm)	Mean nutrient contents (kg ha^{-1})					
			Total	Available	Exchangeable cations			
			N	P	K	Ca	Mg	Na
Bosomoa	teak plantation	11	1,745	42	116	1,164	139	9
	Logged forest.	18	3,184	115	280	2,806	475	13
Tain II	teak plantation	19	3,674	14	216	3,366	485	19
	LogF	17	2,951	18	216	3,278	536	12
Yaya	teak plantation	11	2,044	14	157	2,366	146	5
	LogF.	17	5,868	38	400	4,807	716	6

Table 16. Pooled total nutrients in B-horizons.

Location	Cover type	Mean horizon thickness (cm)	Mean nutrient contents (kg ha^{-1})					
			Total	Available	Exchangeable cations			
			N	P	K	Ca	Mg	Na
Bosomoa	teak plantation	34.8	1,249	26	169	1,351	259	25
	Logged forest.	33.4	1,348	34	210	791	293	34
Tain II	teak plantation	26.0	1,527	13	87	827	239	15
	LogF	21.50	890	5	78	624	171	6
Yaya	teak plantation	26.33	760	6	62	1,014	122	6
	LogF.	30.33	6,122	20	203	643	299	15

Table 17. Pooled total nutrients in (A+B) -horizons.

Location	Cover type	Mean horizon thickness (cm)	Mean nutrient contents (kg ha^{-1}) Total N	Available P	Exchangeable cations K	Ca	Mg	Na
Bosomoa	teak plantation	45.80	2,994	68	285	2,515	398	33
	Logged forest.	51.40	4,532	149	490	3,597	768	47
Tain II	teak plantation	45	5,201	27	303	4,192	723	34
	LogF	38.5	3,841	23	293	3,902	708	19
Yaya	teak plantation	37.33	2,804	20	218	3,380	269	11
	LogF.	47.33	11,990	58	604	5,449	1015	20

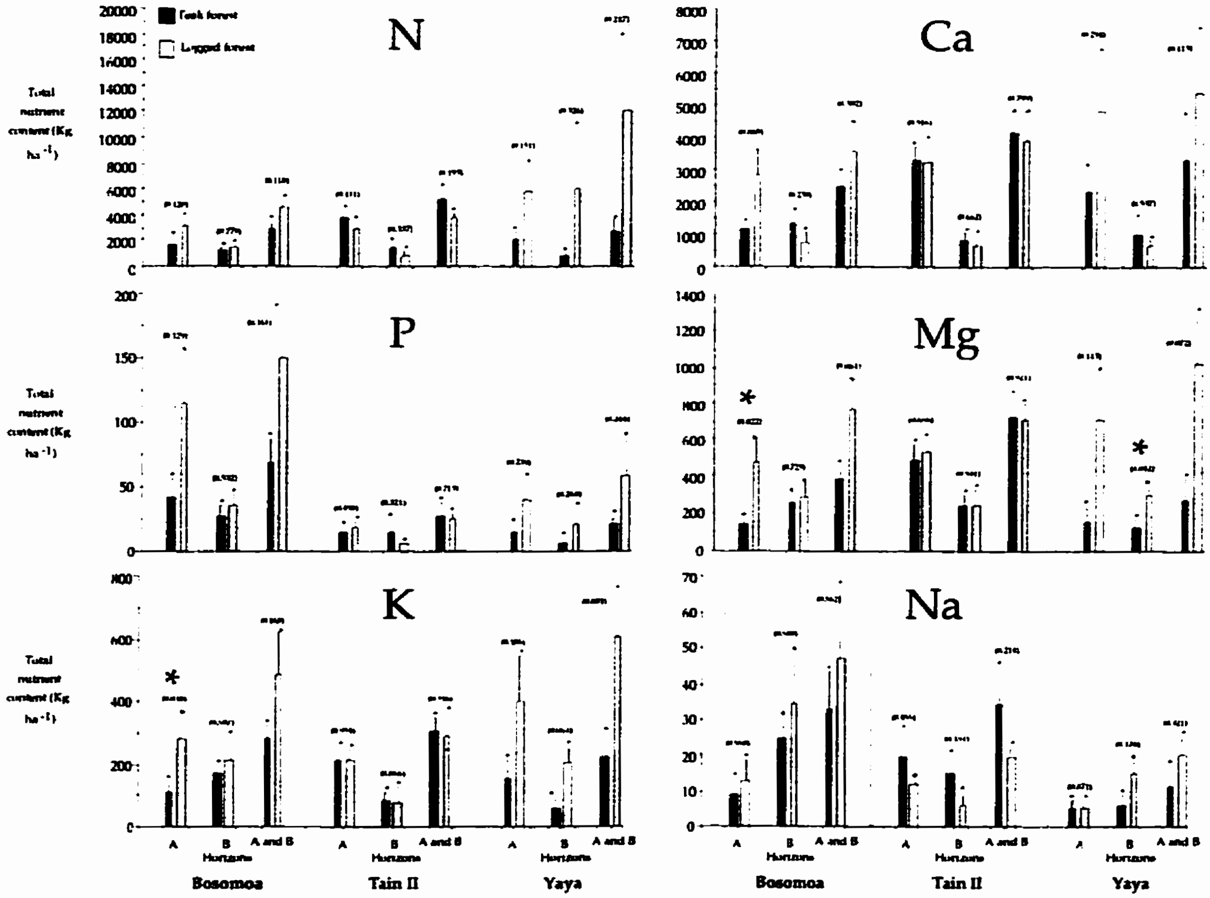

Figure 11. N, P, K, Ca, Mg, and Na contents in A , B and (A+B) horizons, under teak and adjacent logged forests in Bosomoa, Tain II, and Yaya.

Bosomoa

Soil Macro-nutrient contents were generally higher, in the A (Table 15), B (Table 16), and (A+B)-horizons (Table 17) under logged forest than under adjoining teak plantations (Figure 11). The differences observed were not, however, statistically significant except for K and Mg in the A-horizons (Figure 11) and (Table 15). Magnesium was higher ($p < 0.02$) under logged forest (Figure 11), and ranged from 64.98 to 173.02 kg ha^{-1} (138.88) under teak plantation and from 158.23 to 806.41 kg ha^{-1}

(475.46) under logged forest (Table 15). Potassium was higher ($p < 0.03$) under logged forest (Figure 11). Potassium varied from 54.141 to 158.996 kg ha^{-1} (116.0) and from 116.071 to 479.522 kg ha^{-1} (279.67) under teak plantations and under logged forest, respectively (Table 15). The observed differences in Macro-nutrient contents in the B, and (A+B)-horizons (Figure 11) were not statistically significant.

Tain II

Analysis of variance showed that there were no significant differences in computed soil macro-nutrient contents under teak plantations and under adjoining logged forest in the A (Table 15), B (Table 16), and (A+B)-horizons (Table 17) and (Figure 11).

Yaya

Nutrient contents, generally were higher under logged forest than under teak plantations in the A (Table 15), B (Table 16), and (A+B)-horizons (Table 17) and (Figure 11). The differences observed, however, were not significant except for Mg which was statistically significantly higher ($p< 0.04$) in the B-horizon (Table 16) under logged forest (Figure 11).

4.3. COMPARISON OF TEAK/LOGGED FOREST PAIRED MEANS

4.3.1. Individual Paired Compartments - teak plantations and native logged forest

A summary were compared of soil physico-chemical properties under individual teak plantation/logged forest in Bosomoa (Appendices X and XI), Tain II (Appendices XII and XIII), and Yaya (Appendices XIV and XV.).

Soil texture was found to be similar under both teak and adjacent native logged forest, and macro-nutrient concentrations were generally higher under logged forest both in the Bosomoa (Appendices X and XI) and Yaya (Appendices XIV and XV) forest reserves. However, exchangeable Na was found to be higher under the teak plantations of compartments 28 and 33 of Yaya (Appendix XV).

In the Tain II, soil texture was similar under both teak and adjacent native logged forest (Appendix XII). However, OM content and exchangeable nutrients (*e.g.* Ca, Mg, K, Na) were higher under teak plantations except for compartment 280 where Ca, Mg and K were found to be higher under adjacent logged native forest (Appendix XIII).

These comparisons were based on the means for the (A+B) horizons together and for the A and B horizons separately. Both comparisons led to similar conclusions.

4.3.2. Individual Paired Compartments - Thinned and Unthinned teak

The soil was loam under unthinned teak compartment and varied from loam to clay loam under thinned teak compartment (Appendix XII). Soil physical properties were similar under both thinned and unthinned teak compartments except for percent clay and for percent sand. Percent clay was higher ($P<0.02$) under unthinned teak compartment and increased with depth under both thinned and unthinned teak compartments (Appendix XII). Percent sand was higher ($P<0.0001$) under thinned teak compartment (Appendix XII).

Calcium, Mg, and OM content were higher ($P<0.0306$, $P<0.0134$, and $P<0.0000$,) respectively, under the unthinned teak compartment (Appendix XIII). Phosphorus concentration was higher ($P<0.0001$) under the thinned teak compartment (Appendix XIII).

Computed nutrient contents gave higher Na, Ca and Mg values under the unthinned teak compartment, and higher values of K and P under the thinned teak compartment.

4.4. MODELING BULK DENSITY UNDER TEAK PLANTATION

Regression analyses using the backward elimination method of variable selection was used to model Db as a function of variables such as OM, pH, clay, sand, silt, volume of coarse fragments (Vcf) and soil depth. The 0.05 significance level was used to select variables to be included in any given model used for Db predictions. Variables that met the above criteria for each of the models are given in Table 18.

Table 18. Variables included in the multiple regression models for predicting Db.

Model[1]	Physico-chemical variables			
B1	pH[2]	OM (%)[3]	silt (%)	
B2	pH	OM (%)	clay (%)	silt (%)
T1	OM (%)	clay (%)		
T2	OM (%)	Vcf[4]		

[1] B1 and B2 are for the A and B horizons, respectively in Bosomoa and T1 and T2 for A and B horizons, respectively in Tain II.

[2] pH (measured in 0.1 M $CaCl_2$)

[3] Organic matter

[4] Vcf (volume of coarse fragments in cm^3)

Model analysis using dummy variables (Draper and Smith 1966) was used to test whether the soils from Bosomoa and Tain II could be combined to model Db. Results indicated soils from each location required a separate regression model for Db. The same result was obtained at each of the locations when the A and B horizons were tested to see whether they could be combined to predict Db.

Bulk densities were variable and higher at Bosomoa than at Tain II (Table 19). Variability of Db at Bosomoa, was higher in the A-horizons and decreased with depth (Table 19).

Table 19. Sample size (n), mean, range and coefficient of variation (CV%) for Db, OM, pH, Clay, Vcf and silt by sampling layer.

					Range		
Location	Horizon	Variable	n	Mean	Lower	Upper	CV%
Bosomoa	A	Db	10	1.33	1.04	1.53	11.28
	A	OM	10	3.39	1.80	6.60	42.77
	A	pH	10	5.95	5.08	7.06	10.92
	A	silt	10	13.41	9.50	22.55	26.40
	B	Db	10	1.45	1.34	1.62	5.52
	B	OM	10	2.20	1.00	4.30	54.09
	B	clay	10	8.26	2.64	18.54	65.50
	B	pH	10	5.25	4.62	6.42	10.29
	B	silt	10	13.67	9.53	17.88	17.63
Tain II	A	Db	12	1.23	0.79	1.67	20.33
	A	OM	12	8.32	3.00	13.50	35.70
	A	clay	12	14.29	7.91	22.23	34.99
	B	Db	12	1.16	0.57	1.60	33.62
	B	OM	12	5.95	2.20	11.40	46.84
	B	Vcf	12	23.53	0.00	54.00	94.65

Four regression models were developed, models B1 and B2 for Bosomoa are presented in Table 20, and models T1 and T2 for Tain II are given in Table 21. No regression model was developed for Yaya due to the small sample size (n = 6). The model assumptions of homoscedasticity for B1 (Appendix XIXb), B2 (Appendix XXb), T1 (Appendix XXIb), and T2 (Appendix XXIIb), and normality of residuals for B1 (Appendix

XIXc and d), B2 (Appendix XXc and d), T1 (Appendix XXIc and d), and T2 (Appendix XXIIc and d) were met by the four models developed. Residual statistics have been presented for models B1 (Appendix XIXa), B2 (Appendix XXa), T1 (Appendix XXIa), and T2 (Appendix XXIIa). The residual statistics show that no outliers were contained in the data set. However, two influential values, one in (Appendix XIXb) and the other in (Appendix XXb), were accommodated in models B1 and B2, respectively. The influential points were associated with the small sample size.

The partial correlation coefficients (Table 22) indicate the important effects of Clay, Vcf, OM, and Silt on Db. OM, silt and pH were the most important variables for predicting Db at Bosomoa (model B1), (Table 20). Db was significantly inversely related to OM ($r = -0.89$), pH ($r = -0.84$) and was positively correlated with silt ($r = 0.72$) in the A-horizon (Table 22). The arcsin transformation of OM and the natural log of silt improved the predictive power of model B1 (Table 20). The R^2 indicated that model B1 accounts for up to 92% of the variation in Db for the A-horizon at Bosomoa (Table 20).

In the B-horizon, OM, silt, pH and clay were the important predictor variables for Db at Bosomoa. The natural log transformation of OM and √pH improved prediction of Db (model B2). Model B2 explains 98% of the variation in Db for the B-horizon at Bosomoa (Table 20).

Table 20. Regression coefficients and related statistics for models of Db in the A and B horizons at Bosomoa.

	Regression coefficients								Goodness of fit statistics		
		Independent variables									
Model	Intercept	Arcsin (OM)	Clay	Ln(OM)	silt	pH	Ln(silt)	√pH	R^2	SE*	n
B1	1.75^{a}	-7.21^{b}	-	-	-	-0.17^{b}	0.32^{c}	-	0.92^{b}	0.05	10
B2	2.43^{a}	-	0.03^{a}	-0.21	-0.001	-	-	-0.5	0.98^{b}	0.02	10

* SE = standard error of the estimate for the model, a = $P < 0.001$, b = $P < 0.01$, c = $P < 0.05$.

At Tain II, percent OM, clay and Vcf were the most important predictor variables for modeling Db (Table 21). Bulk density was inversely correlated with OM in the A and B horizons ($r = -0.79$ and $r =- 0.50$ respectively). Bulk density had a positive correlation with clay ($r = 0.81$) in the A-horizon and a negative correlation with Vcf ($r = - 0.97$) in the B-horizon (Table 22).

The Arcsin transformation of OM and the inverse √Clay improved prediction of Db in the A-horizon at Tain II, model T1 (Table 21). Model T1 explains 80% of the variation in Db for the A-horizons (Table 20). OM and Vcf were important for predicting Db in the B-horizon, model T2, which accounts for 97% of the variation in Db (Table 21).

Table 21. Regression coefficients and related statistics for models of Db in the A and B horizons at Tain II.

	Regression coefficients					Goodness of fit statistics		
		Independent variables						
Model	Intercept	Vcf	1/ √clay	OM	Arcsin (OM)	R^2	SE	n
T1	2.81^a	-	-10.69^b	-	-8.91^b	0.80^a	0.12	12
T2	1.48^a	-0.02^a	-	0.02	-	0.97^b	0.08	12

a = $P < 0.001$
b = $P < 0.01$
c = $P < 0.05$

Table 22. Partial Correlation Coefficients between Db with Clay, Vcf, OM, pH and Silt in A and B-horizons at Bosomoa, and at Tain II controlling for all other variables included in the models, respectively.

Location/ model	Dependent variable	Clay	Vcf	OM	pH	Silt
Bosomoa						
B1	Db	-	-	-0.8875^b	-0.8420^b	0.7207^c
B2	Db	0.9878^a	-	-0.9553^a	-0.9488^a	-0.9499^a
Tain II						
T1	Db	0.8151^b	-	-0.7904^b	-	-
T2	Db	-	-0.9734^a	0.5007	-	

a= correlation is significant at the 0.001 level (2-tailed)
b= correlation is significant at the 0.01 level (2-tailed)
c= correlation is significant at the 0.05 level (2-tailed)

5.0 DISCUSSION

For this discussion, it was assumed that any differences in observed soil properties represent the properties as might have been modified by:

1) the vegetation growing on them, and/or
2) by the overall management techniques used for establishing the plantations.

5.1. PHYSICAL PROPERTIES

The soil textural class was loamy sand, loam and sandy loam under both forest covers at Bosomoa, Tain II and Yaya, respectively. Analysis of variance (ANOVA) showed there were no significant differences in soil physical properties under teak/logged forest pairs at Bosomoa and at Tain II. Similarly, ANOVA indicated soils were similar under teak/logged forest pairs in the A-horizon at Yaya. In the B-horizon at Yaya, percent clay and Db were significantly higher under logged forest, while percent sand was significantly higher under teak plantation. There was a general translocation of clay from A to B-horizons under both ecosystems in the Tain II and Yaya studied locations, resulting in higher clay contents in the B-horizons. A translocation of clay down the soil profile by water was similarly reported by (Prasad *et al.* 1985). Percent sand was higher at Bosomoa compared to Tain II and Yaya. Higher percent sand at Bosomoa is due to the dominance of quartz sized minerals at Bosomoa as was indicated by clay mineralogy analysis in this study.

Soils were more compacted at Bosomoa than at Tain II and at Yaya. Higher Db's at Bosomoa may be due to the exposure of Bosomoa to intense bush fires in 1994 (Diabore June1997, Pers. com.), that resulted in lower OM content of soils at Bosomoa, hence the higher bulk densities. These results were similarly found by Bell (1973), Chunkao *et al.* (1976), Karunakaran (1984), and Kushalappa *et al.* (1987). Bulk densities were lower in the surface soil and increased with depth under both teak/logged forest pairs at Bosomoa, and the logged forest pair of Yaya. Bulk density has often been found to be strongly correlated with soil OM and texture (Alexander *et al.* 1981, Grigal *et al.* 1989, Huntington *et al.* 1989, Manrique and Jones 1991). The decrease in OM with depth, therefore, resulted in increased Db with depth (Griffith 1942, Laurie and Griffith 1942, Aborisade and Aweto 1990, Mongia and Bandyopadhyay 1992). Furthermore, Manrique and Jones (1991) explained that increasing Db's with depth is partly attributed to the higher OM content in the surface soil and partly to tillage practices that cause relatively loose structure in the surface soil and compaction in the subsoil. At Tain II and Yaya, Db was higher in the surface soil and decreased with depth, and was probably more related to particle size distribution since Db was found to be negatively correlated with volume of coarse fragments.

5. 2. CHEMICAL PROPERTIES

Soil nutrients were generally higher in the A-horizons and decreased with depth. Higher nutrients in the topsoil may be attributed to the higher OM content in the surface soil, and is consistent with the findings of (Ahn 1962). Ahn (1962) further documented that soil nutrients in Ghana were largely stored in the topsoil, wood and foliage of the trees and maintained by the biogeochemical cycle. Soil pH generally decreased with depth at each of the studied locations. This confirms the findings of Alexander *et al.* (1981) and Totey *et al.* (1986). Soil K, Mg, OM, and N concentrations were higher under logged forest at Bosomoa. All chemical parameters were similar under both ecosystems at Tain II. At Yaya, however, Mg and N concentrations, and OM content were higher under logged forest when the A-horizons were considered. The higher nutrient concentrations under logged forest at each of the locations is associated with more undergrowth, litter and OM under logged forest compared with teak plantation, and perhaps, to a lower demand of these nutrients by tree species in logged forest. These results were similar to those found by Griffith (1942), Laurie and Griffith (1942), Aborisade and Aweto (1990), and Mongia and Bandyopadhyay (1992). The low soil nutrient levels found under teak may be due to higher demand and nutrient immobilization in teak (Nwoboshi 1984, Chava and Pandit 1989, Aborisade and Aweto 1990).

In the B-horizons, higher soil Ca and Na levels under teak plantations at Tain II may be attributed to the active role of teak in pedogenesis (Totey *et al.* 1986, Choubey *et al.* 1987, and George and Varghese 1990). Soil pH was higher under teak at Bosomoa and Yaya. Higher soil pH under teak may be attributed to the higher Ca concentrations in the B- horizons at Bosomoa and Yaya. In Liberia, Zech and Drechsel (1991) found a significant positive correlation between soil Ca and pH under teak but not under natural forest.

5.3. MACRO-NUTRIENT CONTENTS

Computed soil macro-nutrient contents were generally higher under logged forest than under teak plantations at Bosomoa and Yaya. The observed differences were not, however, statistically significant except for K, and Mg in the A-horizon at Bosomoa, and Mg in the B-horizon at Yaya. Higher macro-nutrients under logged forest was associated with more undergrowth, litter and OM, and may be to a lesser nutrient demand by species in logged forest (Nwoboshi 1984, Chava and Pandit 1989, Aborisade and Aweto 1990). In the Tain II, soil total macro-nutrients were similar under the two studied ecosystems.

A teak plantation age series was studied in Nigeria for soil nutrients (Nwoboshi 1984), results showed that soil P, N and Ca, were channeled to foliage in early years and that nutrients channeled to trunk and branches increased with age

Large amounts of Ca were stored in the bark of teak, compared to the smaller amounts stored in the bark free bole (Nwoboshi 1984, Zech and Drechsel 1991). Calcium was found to range from (400-427 kg ha^{-1}) in the bark of teak, and smaller amounts were found in the bark free bole (about 166 kg ha^{-1})(Kaul *et. al.* 1979). Therefore, tree harvesting had the potential for site nutrient depletion. Hase and Foelster (1983) found that the removal of teak wood resulted in losses of 220-3,070 Ca kg ha^{-1} in 50-year rotations and decreased soil pH and biological activity. This means that total Ca reserves in the soils of the Bosomoa teak plantation (2,515 kg ha^{-1}), Tain II teak plantation (4,192 kg ha^{-1}), and for the Yaya teak plantation (3,380 kg ha^{-1}) could sustain teak growth for the first 50 years. However, teak harvesting could potentially deplete soil Ca reserves in the second rotation of teak with a consequent reduction in site productivity, and in teak growth. Hase and Foelster (1983) found that teak harvest in Venezuela resulted in considerable loss of soil Ca through biomass removal, and loss of N, S, and K through leaching and erosion (McColl and Powers 1984, Balagopalan 1987). Furthermore, it is generally feared that large teak plantations could lead to soil deterioration through increased soil erosion (Kadambi 1972, White 1991) and soil compaction and a consequent decrease in aeration (Laurie and Griffith 1942, Aborisade and Aweto 1990, Mongia and Bandyopadhyay 1992). The results of total macro-nutrient contents is consistent with the general trends observed in the results of nutrient concentrations discussed above. However, it is noted that the estimates in this thesis are based solely on soil reserves and do not consider other nutrient inputs (*e.g.*, from rain, dust, weathering, *etc.*) and outputs (*e.g.*, through leaching, fire, erosion, *etc.*) from the geochemical cycle that may occur over time (Kimmins 1987).

5.4. THINNED AND UNTHINNED COMPARTMENTS

Percent clay was higher under the unthinned teak compartment. This is because weathering processes were more active under unthinned teak compartment. Increasing clay content with depth is attributed to movement of clay down the profile by rain water *i.e.* illuviation. Soil calcium, Mg and OM content were higher under the unthinned teak compartment due to higher densities of trees in the unthinned compartment (Singh *et al.* 1986, 1988). Higher nutrient contents under unthinned compartment was also associated with higher number of trees (Table 1), and OM under unthinned compartment. These results have been similarly found by (Singh *et al.* 1986, 1988).

5.5. MODELED BULK DENSITY UNDER TEAK PLANTATION

Previous studies have shown highly significant relationships between soil OM, pH, clay and silt contents with Db (Alexander 1980, Jones 1983, Manrique and Jones 1991, Tamminen and Starr 1994). Adams (1993) and Alexander (1980) have shown that bulk densities are related to soil OM in a non-linear fashion. Results from this study, however, indicate that the relationship between Db and soil OM is more linear than reported in other studies (Alexander *et al.* 1981, Grigal *et al.* 1989, Tamminen and Starr 1994). The observed linear relation between Db and OM may be due to the narrower range in OM $\leq$ 10% in this study (Table 19) as has been similarly suggested by Tamminen and Starr (1994).

Bulk density averages well lower in the topsoil at Bosomoa and increased with depth (Table 19), and is partly due to the higher OM content in the topsoil and to tillage practices that cause relatively loose structure in the surface soil and compaction in the subsoil (Manrique and Jones 1991). Bulk density was, however, least variable in the A-horizons at Tain II and variability increased with depth (Table 19). This could be explained by the increasing errors in the estimation of soil volume associated with higher coarse fragments volumes in the lowest depth strata (Huntington *et al.* 1989). Bulk density was highly negatively correlated ($r = -0.97$) with volume of coarse fragments and tended to decrease with increasing particle size. Bulk density was higher in the topsoil and decreased with depth as particle size increased. A plausible explanation for decreasing Db with depth (Kimmins 1978, 1994) is historical vehicular traffic.

The mean bulk densities of soil in the A and B-horizons were 1.33 and 1.45, respectively at Bosomoa, and 1.23 and 1.16, respectively at Tain II (Table 19). The differences in bulk densities amongst the soils from the two locations are primarily due to differences in particle size distribution (Manrique and Jones 1991).

The high R^2 value of the regression equations for models B1, B2, T1, and T2 suggest that Db can be accurately predicted using OM , silt, and pH for model B1; OM, silt, pH, and clay for model B2; OM and clay for model T1; and OM and Vcf for model T2. These results are consistent with reported relationships between Db and the predictor variables (Alexander *et al.* 1981, Grigal *et al.* 1989, Huntington *et al.* 1989, Manrique and Jones 1991, Tamminen and Starr 1994).

The variability in the predictive powers for models B1 and B2 (Table 20) were less than for T1 (Table 21), and may be due to the different particle size distributions at Bosomoa and at Tain II (Manrique and Jones 1991). The soils used for Models B1 and B2 were developed for fine sand which had no coarse fragments. Models T1 and T2 were, however, developed for stony soils with coarse fragments. The high variability in model T1, therefore, could be associated with the increasing errors in estimation of coarse fragment volume (Huntington *et al.* 1989). The unexplained variations in the models could be due to factors associated with the management history of the plantations which were not considered in the analysis. The usefulness, and the applicability of these models is limited by the small sample size and number of study locations. If these models are validated through further sampling, however, they could serve as useful models to predict Db in these and other locations with similar soil conditions.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The following general conclusions were drawn from this study:

1) Within each of the three study locations, there were no significant differences in texture, geology, topography, and fire incidence between the teak/logged forest pairs. From this it was concluded that the study pairs were on comparable sites. It is noted that the findings for soil properties attributed to the teak plantations may also include changes that occurred during the site preparation and establishment of the teak.

2) In general, higher nutrient concentrations and contents were observed in soils under logged forest within location. This was attributed to more undergrowth, litter and OM compared to the teak, and may be to a lesser demand for these nutrients by tree species in logged forest.

3) Lower nutrient concentrations and contents in soils under teak plantations within location was due to lower OM content, and probably due to higher nutrient demand and nutrient immobilization by teak.

4) Less significant differences between teak/logged forest pairs were found within location when total nutrient contents were analyzed rather than just concentrations. This indicated the importance of measuring not only nutrient contents, but also physical factors (obtained mainly in the field) such as depth of rooting, coarse fragment content and Db.

5) It is believed that nutrient immobilization in teak plantations and biomass removal has the potential for site nutrient depletion. Consequently, productivity of site and plantations could decline in subsequent rotations of teak.

6) Db of soils under teak can be reasonably predicted, using OM and particle size distribution as predictor variables. Four explanatory models were developed (Models B1 and B2), Table 20 , and (Models T1 and T2), Table 21. These models will be very useful in explaining Db at the respective studied locations.

7) From the one stand of unthinned teak there seemed to be an indication of increased nutrient loss under the thinned versus unthinned teak. However, further studies will be needed to examine this.

It is recommended that:

1) Similar and more comprehensive studies should be conducted to provide more data to compare, validate and improve upon the insights gained in this study,

2) Comprehensive studies be conducted to:
    i) Compare foliar and soil chemical analysis; this will enhance objective assessments of nutrients tied up in standing biomass and that under forest cover. It will also facilitate the assessment of potential nutrient exports by biomass removal.
    ii) Assess various geochemical inputs (rain, dust, weathering *etc.*) and outputs (leaching, erosion, *etc.*).
    iii) Ascertain most suitable crop type for admixture with teak plantations, and

3) Studies be installed in forested areas prior to establishment of teak plantations. Such studies would compare physico-chemical soil characteristics (a) prior to conversion, (b) immediately after conversion, and (c) at various periods of plantation development. This will help differentiate soil changes due to site preparation as compared to soil changes directly attributable to teak cover.

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APPENDICES

APPENDIX I

SOIL CHEMICAL PROPERTIES UNDER TEAK/LOGGED FOREST PAIRS. BOSOMOA.

Cpt N0	Cover type	Horizon	cmol(+)kg^{-1}						% Base saturation
			Al	H	Fe	Mn	Zn	ECEC	
43	Teak	A	0.000	0.001	0.001	0.034	0.000	2.980	98.16
		B1	0.004	0.002	0.001	0.045	0.001	1.480	94.25
	LogF.	A	0.007	0.004	0.002	0.047	0.004	3.480	96.42
		B1	0.005	0.120	0.001	0.049	0.001	0.720	86.54
67	Teak	A	0.007	0.000	0.001	0.028	0.001	6.040	99.15
		B1	0.000	0.004	0.001	0.071	0.001	1.630	93.96
	LogF.	A	0.000	0.000	0.002	0.033	0.001	9.400	99.34
		B1	0.000	0.004	0.001	0.027	0.002	2.300	95.86
68	Teak	A	0.000	0.001	0.001	0.021	0.002	3.230	97.49
		B1	0.002	0.004	0.001	0.069	0.002	1.730	93.08
	LogF.	A	0.008	0.000	0.002	0.017	0.004	7.230	98.79
		B1	0.005	0.003	0.001	0.040	0.001	1.650	92.49
83	Teak	A	0.004	0.000	0.004	0.025	0.000	11.950	99.53
		B1	0.000	0.000	0.002	0.019	0.000	3.630	98.93
	LogF.	A	0.004	0.000	0.004	0.037	0.000	11.210	99.47
		B1	0.009	0.020	0.002	0.035	0.001	1.000	92.76
108	Teak	A	0.007	0.000	0.001	0.021	0.001	4.230	99.20
		B	0.007	0.002	0.001	0.036	0.002	1.720	96.82
	LogF	A	0.012	0.000	0.002	0.018	0.002	8.470	99.46
		B	0.007	0.006	0.001	0.019	0.008	1.920	97.57

APPENDIX II

SOIL CHEMICAL PROPERTIES UNDER TEAK/LOGGED FOREST PAIRS, TAIN II.

Cpt NO.	Cover type	Horizon	cmol(+)kg^{-1}						% Base saturation
			Al	H	Fe	Mn	Zn	ECEC	
146	Teak	A	0.005	0.000	0.002	0.004	0.000	9.640	99.56
		B1	0.000	0.001	0.001	0.017	0.000	4.950	98.87
	LogF.	A	0.004	0.001	0.002	0.035	0.000	6.340	98.81
		B1	0.004	0.013	0.001	0.062	0.002	2.090	95.10
147	Teak	A	0.005	0.000	0.003	0.011	0.001	11.610	99.41
		B1	0.006	0.001	0.002	0.104	0.001	6.320	97.07
	LogF.	A	0.002	0.001	0.002	0.045	0.000	6.710	98.64
		B1	0.005	0.023	0.002	0.072	0.000	2.190	93.72
160	Teak	A	0.010	0.000	0.003	0.001	0.001	18.840	99.73
		B1	0.008	0.000	0.002	0.034	0.000	8.430	98.41
	LogF.	A	0.011	0.000	0.003	0.006	0.001	22.820	99.70
		B1	0.001	0.005	0.002	0.072	0.001	6.430	97.34
242	Teak	A	0.002	0.000	0.001	0.011	0.000	9.250	99.39
		B1	0.002	0.005	0.001	0.016	0.001	3.540	98.38
	uteak	A	0.000	0.000	0.001	0.002	99.82	15.740	99.82
		B1	0.004	0.001	0.001	0.012	99.51	9.930	99.51
	LogF	A	0.000	0.001	0.001	0.021	99.56	8.530	99.56
		B1	0.000	0.001	0.000	0.027	97.96	2.280	97.96
280	Teak	A	0.000	0.001	0.002	0.020	98.42	7.270	98.42
		B1	0.007	0.040	0.001	0.028	94.80	1.700	94.80
	LogF	A	0.007	0.001	0.004	0.059	98.42	11.970	98.42
		B1	0.009	0.032	0.002	0.037	93.15	1.860	93.15
300	Teak	A	0.009	0.000	0.003	0.006	99.73	11.430	99.73
		B1	0.000	0.000	0.001	0.006	98.77	3.580	98.77
	LogF	A	0.009	0.000	0.003	0.002	99.82	18.300	99.92
		B1	0.002	0.001	0.001	0.018	98.77	4.560	98.77

APPENDIX III

SOIL CHEMICAL PROPERTIES UNDER TEAK/ LOGGED FOREST/ PAIRS, YAYA.

Cpt NO.	Cover type	Horizon	cmol(+)kg^{-1}						% Base saturation
			Al	H	Fe	Mn	Zn	ECEC	
28	Teak	A	0.006	0.000	0.002	0.003	0.001	8.67	99.80
		B1	0.006	0.002	0.001	0.005	0.001	2.83	99.12
	LogF.	A	0.011	0.000	0.003	0.004	0.001	12.88	99.82
		B1	0.011	0.020	0.001	0.064	0.002	1.36	92.87
33	Teak	A	0.007	0.000	0.004	0.004	0.001	22.17	99.52
		B1	0.002	0.000	0.002	0.003	0.001	7.30	99.33
	LogF.	A	0.011	0.000	0.005	0.010	0.001	24.22	99.75
		B1	0.000	0.008	0.001	0.024	0.001	3.57	97.50
34	Teak	A	0.007	0.000	0.002	0.009	0.002	8.57	99.59
		B1	0.006	0.001	0.001	0.011	0.001	3.53	99.01
	LogF.	A	0.007	0.000	0.002	0.004	0.001	8.84	99.72
		B1	0.006	0.013	0.001	0.079	0.001	1.80	90.02

APPENDIX IV

SOIL NUTRIENT CONTENTS UNDER TEAK/LOGGED FOREST PAIRS, BOSOMOA.

						Nutrient contents (kgha^{-1})					
						Total	Available	Exchangeable cations			
Cpt .No.	Cover type	Horizon	Thickness (cm)	Db (gcm^{-3})	%CF	N	P	Ca	Mg	k	Na
43	Teak	A	7	1.51	0	4143.00	15.00	486.22	64.98	54.14	4.37
	LogF.	A	12	1.33	0	1484.00	83.00	762.89	158.23	116.07	9.17
67	Teak	A	13	1.24	0	1241.00	76.00	1576.54	170.40	146.86	5.93
	LogF.	A	10	1.22	0	2208.00	36.00	1754.36	262.96	180.79	4.77
68	Teak	A	15	1.38	0	1159.00	42.00	1006.02	143.36	124.64	27.60
	LogF.	A	30	1.12	0	4469.00	273.00	3608.64	576.43	479.52	34.76
83	Teak	A	7	1.15	0	1119.00	12.00	1582.63	173.02	95.37	3.52
	LogF.	A	20	1.46	0	3913.00	78.00	5039.92	806.41	285.43	10.74
108	Teak	A	13	1.36	0	1061.00	64.00	1166.88	142.64	159.00	1.63
	LogF.	A	18	1.31	0	3844.00	103.00	2862.61	573.28	336.52	5.96
43	Teak	B1	23	1.43	0	493.00	16.00	133.74	644.64	127.08	27.22
	LogF.	B1	20	1.52	0	851.00	39.00	96.28	212.80	79.41	16.77
67	Teak	B1	31	1.42	0	1321.00	27.00	185.89	792.36	285.61	21.25
	LogF.	B1	22	1.3	0	1201.00	15.00	127.48	617.76	351.66	39.45
68	Teak	B1	30	1.53	0	1193.00	24.00	166.91	1064.88	195.75	44.32
	LogF.	B1	70	1.34	0	2345.00	63.00	469.45	1819.72	529.95	90.57
83	Teak	B1	23	1.48	0	1362.00	10.00	110.47	2001.55	237.40	12.52
	LogF.	B1	30	1.45	0	1305.00	40.00	134.37	408.90	207.18	13.00
108	Teak	B1	67	1.4	0	1876.00	54.00	249.40	2251.20	449.03	17.25
	LogF.	B1	27	1.48	0	1039.00	13.00	223.43	895.10	295.19	9.19

APPENDIX V

SOIL NUTRIENT CONTENTS UNDER TEAK/LOGGED FOREST PAIRS. TAIN II.

						Nutrient contents (kgha^{-1})					
						Total	Available	Exchangeable cations			
cpt no	Cover type	Horizon	Depth (cm)	Db (gcm^{-3})	%CF	N	P	K	Ca	Mg	Na
146	Teak	A	20	1.38	19	4024.00	16.00	172.20	3331.04	529.40	16.45
	LogF.	A	20	1.29	0	3406.00	24.00	176.54	2239.44	552.02	13.05
147	Teak	A	10	1.23	21.5	2240.00	4.00	99.67	1653.02	319.21	10.88
	LogF.	A	18	1.25	0	3578.00	13.00	158.36	2047.50	517.50	19.14
160	Teak	A	16	1	23.75	3087.00	6.00	401.65	3745.40	385.55	9.26
	LogF.	A	10	1.14	23	2379.00	5.00	322.63	3288.24	329.45	8.07
242	Teak	A	20	1.31	0	2122.00	11.00	160.83	4296.80	273.13	11.44
	LogF.	A	20	1.09	4	3361.00	18.00	150.56	2850.39	380.40	6.74
280	Teak	A	20	1.56	0	6614.00	19.00	214.71	2907.84	880.60	59.53
	LogF.	A	12	1.37	0	4242.00	35.00	183.20	2600.81	729.27	19.65
300	Teak	A	25	0.92	0	3956.00	29.00	247.31	4259.60	520.34	6.87
	LogF.	A	20	1.09	0	741.00	14.00	302.59	6644.64	708.53	8.02
146	Teak	B	28	1.11	72.25	1061.00	2.00	41.14	591.65	141.68	6.54
	LogF.	B1	28	0.86	81.25	248.00	5.00	17.83	94.82	46.30	3.01
147	Teak	B	25	0.74	81.75	317.00	1.00	21.65	272.13	79.58	5.43
	LogF.	B1	22	0.64	74.75	185.00	2.00	14.73	76.08	38.79	2.21
160	Teak	B1	24	0.68	80.75	276.00	1.00	43.73	365.68	81.84	4.48
	LogF.	B1	21	1.47	16.5	2191.00	6.00	319.49	2252.86	507.36	19.56
242	Teak	B1	24	1.35	14.25	3362.00	13.00	124.93	1228.01	398.66	14.69
	LogF.	B1	28	0.5	78	123.00	1.00	3.01	93.63	26.23	0.92
280	Teak	B1	30	1.55	21.5	2446.00	49.00	145.58	547.54	341.06	26.85
	LogF.	B1	10	1.47	52	593.00	10.00	29.80	111.48	73.30	6.16
300	Teak	B1	25	1.51	0	1699.00	11.00	147.60	1955.45	388.49	32.11
	LogF.	B1	20	1.3	27.5	1998.00	5.00	82.55	1112.15	335.98	6.07

APPENDIX VI

SOIL NUTRIENT CONTENTS UNDER TEAK/LOGGED FOREST PAIRS, YAYA

						Nutrient contents (kgha^{-1})					
						Total	Available	Exchangeable cations			
Cpt NO	Cover type	Horizon	Depth (cm)	Db (gcm^{-3})	%Cf	N	P	K	Ca	Mg	Na
28	teak	A	15	1.31	7	3063.00	13.00	184.28	2516.04	320.90	2.50
	LogF.	A	30	1.37	0	9617.00	71.00	631.55	8302.20	1181.50	4.72
33	Teak	A	10	1.01	6	2288.00	23.00	231.27	3645.70	33.80	10.70
	LogF.	A	12	0.96	0	5449.00	25.00	431.51	4177.15	710.76	8.74
34	Teak	A	9	1	28.25	781.00	6.00	54.54	936.34	84.58	2.08
34	LogF.	A	10	1.38	0	2539.00	18.00	138.13	1940.28	255.53	3.49
28	teak	B1	30	0.89	26	850.00	5.00	64.12	786.37	175.96	5.00
	LogF.	B1	30	1.6	14.75	15672.00	41.00	139.20	491.04	287.37	6.59
33	Teak	B1	33	1.02	52.75	1225.00	5.00	108.83	1997.59	156.52	12.07
	LogF	B1	28	1.45	36.75	1643.00	11.00	295.20	1037.45	374.10	20.07
34	Teak	B1	16	0.93	69.25	206.00	9.00	11.81	258.98	33.97	1.37
	LogF.	B1	33	1.17	32	1050.00	8.00	175.54	399.07	236.06	17.50

APPENDIX VII

POOLED MEAN OF SOIL TOTAL NUTRIENTS BY LOCATION AND COVER TYPE FOR A-HORIZONS.

			Mean nutrient content (kgha^{-1}) (standard error of mean)					
			Total	Available	Exchangeable cations			
Location	Cover type	Mean horizon thickness (cm)	N	P	K	Ca	Mg	Na
Bosomoa	teak pln.	11	1744.60 (600.31)	41.80 (12.78)	116.00 (18.88)	1163.66 (203.69)	138.88 (19.56)	8. 61 (4.80)
	Logged forest.	18	3183.60 (568.37)	114.60 (41.07)	279.67 (63.15)	2805.68 (738.85)	475.46 (117.28)	13.08 (5.52)
Tain II	teak	19	3673.83 (674.67)	14.17 (3.77)	216.06 (42.41)	3365.62 (406.38)	484.70 (89.81)	19.07 (8.19)
	LogF	17	2951.17 (504.85)	18.17 (4.22)	215.58 (31.17)	3278.50 (696.86)	536.19 (66.98)	12.45 (2.37)
Yaya	teak	11	2044.00 (669.96)	14.00 (4.93)	156.70 (52.85)	2366.03 (785.71)	146.42 (88.46)	5.09 (2.81)
	LogF.	17	5868.33 (2053.97)	38.00 (16.62)	400.40 (143.29)	4806.54 (1863.29)	715.93 (267.32)	5.65 (1.59)

APPENDIX VIII

POOLED MEAN OF SOIL TOTAL NUTRIENTS BY LOCATION AND COVER TYPE FOR B-HORIZONS.

			Mean nutrient content (kgha^{-1}) (standard error of mean)					
			Total	Available	Exchangeable cations			
Location	Cover type	Mean horizon thickness (cm)	N	P	K	Ca	Mg	Na
Bosomoa	teak pln.	34.8	1249.00 (222.01)	26.20 (7.57)	169.28 (23.90)	1350.93 (326.07)	258.97 (54.17)	24.51 (5.51)
	Logged forest.	33.4	1348.20 (260.76)	34.00 (9.23)	210.20 (68.170)	790.86 (281.02)	292.68 (75.03)	33.80 (15.14)
Tain II	teak	26.0	1526.83 (499.59)	12.83 (7.55)	87.44 (23.66)	826.74 (263.84)	238.55 (62.67)	15.02 (4.85)
	LogF	21.50	889.67 (9387.55)	4.83 (1.30)	77.90 (49.63)	623.50 (9365.86)	171.33 (82.44)	6.32 (2.78)
Yaya	teak	26.33	760.33 (297.56)	6.33 (1.33)	61.59 (28.04)	1014.31 (514.67)	122.15 (44.45)	6.15 (3.14)
	LogF.	30.33	6121.67 (4778.23)	20.00 (910.54)	203.31 (947.130)	642.52 (199.24)	299.18 (40.28)	14.72 (4.13)

APPENDIX IX

POOLED MEAN OF SOIL TOTAL NUTRIENTS BY LOCATION AND COVER TYPE FOR (A+B) -HORIZONS.

Location	Cover type	Horizon thickness (cm)	Mean nutrient content (kgha^{-1}) (standard error of mean)					
			Total N	Available P	Exchangeable cations			
					K	Ca	Mg	Na
Bosomoa	Teak pln.	45.80	2993.60 (442.10)	68.00 (19.11)	285.28 (40.70)	2514.59 (452.33)	397.85 (65.98)	33.12 (10.11)
	Logged forest.	51.40	4531.80 (771.01)	148.60 (48.66)	489.87 (128.63)	3596.54 (871.17)	768.14 (156.38)	46.88 (20.11)
Tain II	Teak	45	5200.66 (923.05)	27.00 (9.83)	303.50 (49.46)	4192.36 (622.65)	723.26 (123.75)	34.08 (11.01)
	LogF	38.5	3840.84 (310.94)	23.00 (4.96)	293.48 (77.56)	3902.00 (922.22)	707.52 (94.10)	18.77 (3.10)
Yaya	Teak	37.33	2804.33 (915.97)	20.33 (4.48)	218.29 (80.51)	3380.34 (1284.62)	268.57 (115.99)	11.24 (6.01)
	LogF.	47.33	11990.00 (6726.26)	58.00 (27.22)	603.71 (145.56)	5449.06 (1866.78)	1015.11 (284.18)	20.37 (5.21)

APPENDIX X

SOIL PHYSICAL PROPERTIES UNDER TEAK/ LOGGED FOREST PAIRS BOSOMOA.

Cpt	Cover type	Horizon	Depth (cm)	Soil matrix colour	Sand (%)	Silt (%)	Clay (%)	Textural class	Bulk density
43	Teak	A	0-7	2.5YR4/2 weak red	87.88	10.94	1.19	S	1.51
		B1	7-30	5YR5/6 yellowish red	86.52	10.41	3.08	LS	1.43
	LogF.	A	0-12	2.5YR3/2 dusky red	89.82	6.81	3.37	S	1.33
		B1	12-32	2.5YR3/4 dark reddish brown	92.83	3.37	3.80	S	1.52
67	Teak	A	0-13	5YR4/6 yellowish red	79.01	14.37	6.62	LS	1.24
		B1	13-44	5YR5/6 yellowish red	75.55	17.24	7.22	SL	1.42
	LogF.	A	0-10	5YR3/3 dark reddish brown	69.95	24.59	5.47	SL	1.22
		B1	10-32	10YR5/3 brown	65.44	26.5	8.06	SL	1.30
68	Teak	A	0-15	2.5YR3/4 dark reddish brown	80.67	11.59	7.75	LS	1.38
		B1	15-45	2.5YR4/6 red	76.53	13.42	10.06	SL	1.53
	LogF.	A	0-30	2.5YR3/4 dark reddish brown	82.08	10.60	7.33	LS	1.12
		B1	30-100	7.5YR4/4 black to dark brown	82.34	11.00	6.67	LS	1.34
83	Teak	A	0-7	2.5YR3/6 dark red	70.72	17.94	11.35	SL	1.15
		B1	7-30	2.5YR4/6 red	70.60	12.93	16.48	SL	1.48
	LogF.	A	0-20	2.5YR3/4 dark reddish brown	79.27	14.42	6.32	LS	1.46
		B1	20-50	2.5YR4/6 red	77.45	10.27	12.28	SL	1.45
108	Teak	A	0-13	5YR4/6 yellowish red	84.88	12.20	2.93	LS	1.36
		B1	13-80	5YR5/6 yellowish red	81.15	14.37	4.49	LS	1.40
	LogF.	A	0-18	2.5YR3/3 dark reddish brown	80.01	15.81	4.19	LS	1.31
		B1	18-45	5YR5/6 yellowish red	79.54	16.03	4.44	LS	1.48

APPENDIX XI

SOIL CHEMICAL PROPERTIES UNDER TEAK/ LOGGED FOREST PAIRS, BOSOMOA.

Cpt. N0.	Cover type	Horizon	Cm (%)	Total N (%)	Available P (mgkg^{-1})	Exchangeable cations (cmol(+)kg^{-1}) Ca	Mg	K	Na	pH (Cacl$_2$)
43	Teak	A	2.025	0.392	4.52	2.300	0.506	0.131	0.018	5.33
		B1	1.250	0.015	1.45	0.980	0.318	0.104	0.036	5.23
	LogF.	A	2.380	0.093	16.72	2.390	0.816	0.186	0.025	5.26
		B1	0.860	0.028	3.36	0.350	0.215	0.081	0.024	4.43
67	Teak	A	3.400	.077	15.24	4.890	0.870	0.233	0.016	6.71
		B1	1.850	0.030	1.96	0.900	0.534	0.108	0.021	4.94
	LogF.	A	6.900	0.181	9.44	7.190	1.774	0.379	0.017	6.23
		B1	2.380	0.042	1.70	1.080	1.012	0.114	0.060	4.87
68	Teak	A	2.800	0.056	6.54	2.430	0.570	0.154	0.058	5.37
		B1	2.230	0.026	1.73	1.160	0.351	0.093	0.042	4.87
	LogF.	A	5.800	0.133	26.16	5.370	1.412	0.365	0.045	5.89
		B1	1.530	0.025	2.11	0.970	0.465	0.128	0.042	5.33
83	Teak	A	7.850	0.139	4.61	9.830	1.769	0.303	0.019	6.54
		B1	4.100	0.040	0.85	2.940	0.574	0.083	0.016	6.14
	LogF.	A	9.100	0.134	8.69	8.630	2.273	0.250	0.016	6.04
		B1	3.200	0.030	2.89	0.470	0.392	0.079	0.013	4.11
108	Teak	A	2.800	0.060	11.63	3.300	0.664	0.230	0.004	5.82
		B1	1.850	0.020	1.88	1.200	0.394	0.068	0.008	5.06
	LogF.	A	8.380	0.163	14.15	6.070	2.001	0.365	0.011	6.14
		B1	1.580	0.026	1.10	1.120	0.608	0.143	0.010	4.70

APPENDIX XII

SOIL PHYSICAL PROPERTIES UNDER TEAK/LOGGED FOREST PAIRS . TAIN II.

Cpt. No.	Cover type	Horizon	Depth (cm)	Soil matrix colour	Mechanical analysis (%)			Text class	Db gcm^{1}	CF (%)
					Sand	Silt	Clay			
146	Teak	A	0-20	5YR3/4 dark reddish brown	53.19	33.40	13.42	SL	1.38	19.00
		B1	20-48	2.5YR4/4 reddish brown	50.31	27.72	21.98	SCL	1.11	72.25
	LogF.	A	0-20	5YR3/4 dark reddish brown	53.89	35.79	10.33	SL	1.29	0.00
		B1	20-48	2.5YR4/4 reddish brown	58.16	24.02	17.83	SL	0.86	81.25
147	Teak	A	0-10	2.5YR3/2 dusky red	42.88	40.56	16.57	L	1.23	21.50
		B1	10-35	2.5YR4/4 reddish brown	44.99	31.69	23.32	L	0.74	81.75
	LogF.	A	0-18	2.5YR3/2 dusky red	56.39	34.10	9.51	SL	1.25	0.00
		B1	18-40	2.5YR3/4 dark reddish brown	57.47	25.50	17.03	SL	0.64	74.75
160	Teak	A	0-16	5YR3/2 dark reddish brown	45.43	36.78	17.80	L	1.00	23.75
		B1	16-40	2.5YR3/6 dark-red	43.29	26.86	29.85	CL	0.68	80.75
	LogF.	A	0-10	5YR4/4 reddish brown	41.79	37.94	20.28	L	1.14	23.00
		B1	10-31	2.5YR4/6 red	39.81	35.07	25.12	L	1.47	16.50
242	Teak	A	0-20	5YR3/2 dark reddish brown	47.38	42.87	9.76	L	1.31	0.00
		B1	20-44	5YR4/2 dark reddish grey	45.14	36.69	18.18	L	1.35	14.25
	Uteak	A	0-20	5YR3/4 dark reddish brown	33.66	43.81	22.54	L	1.40	0.00
		B1	20-50	5YR4/4 reddish brown	31.42	36.00	32.59	CL	1.47	55.25
	LogF.	A	0-20	2.5YR3/4 dark reddish brown	50.22	33.25	16.54	L	1.09	4.25
		B1	20-48	2.5YR3/6 dark red	64.90	20.87	14.24	SL	0.50	78.00
280	Teak	A	0-20	2.5YR3/4 dark reddish brown	35.16	45.02	19.83	L	1.56	0.00
		B1	20-50	5YR4/6 yellowish red	28.36	32.96	38.69	CL	1.55	21.50
	LogF.	A	0-12	2.5YR3/4 dark reddish brown	42.90	44.71	12.40	L	1.37	0.00
		B1	12-22	5YR4/6 yellowish red	33.19	40.80	26.02	CL	1.47	52.00
300	Teak	A	0-25	2.5YR3/4 dark reddish brown	62.20	29.42	8.36	SL	0.92	0.00
		B1	25-50	2.5YR4/4 reddish brown	54.07	34.09	11.85	SL	1.51	0.00
	LogF.	A	0-20	2.5YR3/4 dark reddish brown	50.34	39.41	9.26	SL	1.09	0.00
		B1	20-40	2.5YR4/8 red	44.87	39.43	15.71	L	1.30	27.50

APPENDIX XIII

SOIL CHEMICAL PROPERTIES UNDER TEAK/LOGGED FOREST PAIRS .TAIN II.

			OM	Total N	Available P	Exchangeable nutrients cmol (+) kg^{-1}				pH
Cpt. NO.	Cover type	Horizon	(%)	(%)	(mg kg^{-1})	Ca	Mg	K	Na	Cacl$_2$
146	Teak	A	8.025	0.180	2.32	7.450	1.949	0.197	0.032	5.81
		B1	5.430	0.123	0.56	3.430	1.352	0.122	0.033	5.45
	LogF.	A	6.730	0.132	2.93	4.340	1.761	0.175	0.022	5.55
		B1	5.250	0.055	3.60	1.050	0.844	0.101	0.029	4.30
147	Teak	A	10.23	0.232	1.39	8.560	2.721	0.264	0.049	6.07
		B1	7.600	0.094	0.77	4.030	1.940	0.164	0.070	5.68
	LogF.	A	6.180	0.159	1.92	4.550	1.893	0.180	0.037	5.31
		B1	5.250	0.052	2.04	1.070	0.898	0.106	0.027	4.05
160	Teak	A	10.98	0.253	1.59	15.35	2.601	0.842	0.033	6.93
		B1	9.800	0.088	1.03	5.820	2.144	0.356	0.062	6.46
	LogF.	A	10.83	0.271	2.01	18.73	3.089	0.940	0.040	7.07
		B1	6.530	0.085	0.77	4.370	1.620	0.317	0.033	5.18
242	Teak	A	3.930	0.081	1.34	8.200	0.858	0.157	0.019	6.65
		B1	3.550	0.121	1.59	2.210	1.181	0.115	0.023	5.50
	uteak	A	9.980	0.130	0.59	13.83	1.751	0.133	0.021	5.95
		B1	8.430	0.088	0.33	8.150	1.593	0.145	0.026	5.62
	LogF	A	8.280	0.161	2.75	6.810	1.496	0.184	0.014	6.00
		B1	4.380	0.040	1.33	1.520	0.701	0.025	0.013	5.32
280	Teak	A	8.430	0.212	1.96	4.660	2.323	0.176	0.083	5.51
		B1	7.480	0.067	4.34	0.750	0.769	0.102	0.032	3.80
	LogF	A	12.23	0.258	6.83	7.910	3.651	0.285	0.052	5.81
		B1	7.100	0.084	4.44	0.790	0.855	0.108	0.038	3.90
300	Teak	A	6.400	0.172	4.06	9.260	1.862	0.275	0.013	6.79
		B1	2.930	0.045	0.98	2.590	0.847	0.100	0.037	6.04
	LogF	A	16.33	0.034	2.07	15.24	2.675	0.355	0.016	7.01
		B1	5.050	0.106	0.87	2.950	1.467	0.112	0.014	5.80

Uteak= unthinned teak plantation.

APPENDIX XIV

SOIL PHYSICAL PROPERTIES UNDER TEAK/ LOGGED FOREST PAIRS. YAYA.

Cpt. No	Cover type	Horizon	Depth cm	Soil matrix colour	Mechanical analysis (%) sand	silt	clay	Text. Class	Db gcm^{-3}	CF (%)
28	teak	A	0-15	2.5YR3/4 dark reddish brown	71.08	19.80	9.13	SL	1.31	7.75
		B1	15-45	2.5YR4/4 reddish brown	69.55	14.11	16.35	SL	0.89	26.00
	LogF.	A	0-30	2.5YR3/4 dark reddish brown	66.70	24.63	8.68	SL	1.37	0.00
		B1	30 +	2.5YR4/6 red	55.27	17.74	27.00	SCL	1.60	14.75
33	Teak	A	0-10	5YR3/4 dark reddish brown	61.68	23.89	14.43	SL	1.01	6.00
		B1	10-43	5YR4/6 yellowish red	63.69	16.85	19.47	SL	1.02	52.75
	LogF.	A	0-12	5YR4/3 reddish brown	50.52	31.32	18.17	L	0.96	0.00
		B1	12-40	5YR4/6 yellow red	58.59	17.07	24.34	SCL	1.45	36.75
34	Teak	A	0-9	2.5YR3/2 dusky red	70.47	20.07	9.47	SL	1.00	28.25
		B1	9-25	5YR4/4 reddish brown	68.22	14.26	17.53	SL	0.93	69.25
	LogF.	A	0-10	2.5YR3/4 dark reddish brown	73.73	17.12	9.16	SL	1.38	0.00
		B1	10-43	5YR4/6 yellowish red	63.47	15.06	21.48	SCL	1.17	32.00

APPENDIX XV

SOIL CHEMICAL PROPERTIES UNDER TEAK/LOGGED FOREST PAIRS, YAYA.

			OM	Total N	Avail P	Exchangeable nutrients cmol (+) kg^{-1}				pH Cacl2
Cpt. NO.	cover type	Horizon	(%)	(%)	(mg kg^{-1})	Ca	Mg	K	Na	
28	Teak	A	7.950	0.169	2.32	6.940	1.457	0.260	0.006	6.35
		B1	4.500	0.043	0.79	1.990	0.733	0.083	0.011	5.34
	LogF.	A	10.780	0.234	5.54	10.10	2.366	0.393	0.005	6.58
		B1	6.100	0.383	3.26	0.600	0.578	0.087	0.007	4.11
33	Teak	A	11.330	0.241	7.96	19.20	0.293	0.623	0.049	7.18
		B1	6.380	0.077	1.02	6.280	0.810	0.175	0.033	7.16
	LogF.	A	19.050	0.473	7.10	18.13	5.078	0.958	0.033	6.58
		B1	6.480	0.064	1.35	2.020	1.199	0.294	0.034	4.89
34	Teak	A	6.700	0.121	2.82	7.250	1.078	0.216	0.014	5.88
		B1	5.330	0.045	5.96	2.830	0.611	0.066	0.013	5.43
	LogF.	A	9.700	0.184	4.11	7.030	1.524	0.256	0.011	6.85
		B1	5.100	0.040	0.89	0.760	0.740	0.171	0.029	4.60

APPENDIX XVI

POOLED MEANS OF SOIL PHYSICAL PROPERTIES BY LOCATION AND COVER TYPE.

			Particle size distribution (standard error of mean) (%)			
Location Cover type	Horizon	Textural class	Sand	Silt	Clay	Bulk density (g cm^{-1})
Bosomoa						
Teak	A	LS	81	13	6	1.33
			(2.00)	(1)	(1)	(0.05)
	B	LS	78	14	8	1.45
			(2.00)	(1)	(2)	(0.03)
Logged forest	A	LS	81	14	5	1.29
			(2)	(2)	(1)	(0.05)
	B	LS	81	12	7	1.42
			(3)	(3)	(1)	(1.03)
Tain II						
Teak	A	L	48	38	14	1.23
			(3)	(2)	(1)	(0.07)
	B	L	44	32	24	1.16
			(3)	(1)	(3)	(0.11)
Logged forest	A	L	49	38	13	1.20
			(2)	(1)	(1)	(0.05)
	B	L	50	31	19	1.04
			(4)	(2)	(2)	(0.13)
Yaya						
Teak	A	SL	68	21	11	1.10
			(2)	(1)	(1)	(0.09)
	B	SL	67	18	15	0.94
			(2)	(2)	(1)	(0.05)
Logged forest	A	SL	64	24	12	1.24
			(5)	(3)	(2)	(0.09)
	B	SL	59	25	16	1.40
			(2)	(1)	(1)	(0.08)

APPENDIX XVII

POOLED MEANS OF SOIL CHEMICAL PROPERTIES BY LOCATION AND COVER TYPE.

		Exchangeable cations cmol (+) kg^{-1} (SE)				Percent total	Percent	pH
Location/ Cover type	Avail. P ($mgkg^{-1}$)	K	Ca	Mg	Na	N	OM	$CaCl_2$
Bosomoa								
Teak								
A	8.51	0.21	4.55	0.88	0.02	0.07	3.78	5.95
	(1.48)	(0.02)	(0.81)	(0.12)	(0.00)	(0.01)	(0.54)	(0.21)
B	1.57	0.09	1.43	0.43	0.02	0.03	2.25	5.25
	(0.16)	(0.01)	(0.02)	(0.03)	(0.00)	(0.00)	(0.24)	(0.17)
Logged forest								
A	15.11	0.30	5.76	1.61	0.02	0.14	6.31	5.85
	(1.99)	(0.030	(0.73)	(0.14)	(0.00)	(0.01)	(0.84)	(0.17)
B	2.28	0.11	0.77	0.52	0.03	0.03	1.86	4.66
	(0.25)	(0.01)	(0.13)	(0.07)	(0.01)	(0.00)	(0.21)	(0.17)
Tain II								
Teak								
A	2.11	0.32	8.91	2.05	0.04	0.19	8.00	6.29
	(0.23)	(0.05)	(1.10)	(0.15)	(0.01)	(0.02)	(0.55)	(0.18)
B	1.55	0.16	3.14	1.37	0.04	0.09	6.13	5.49
	(0.32)	(0.02)	(0.45)	(0.13)	(0.00)	(0.02)	(0.52)	(0.30)
Logged forest								
A	3.09	0.35	9.60	2.43	0.03	0.22	10.09	6.12
	(0.49)	(0.07)	(1.52)	(0.23)	(0.00)	(0.02)	(0.88)	(0.22)
B	2.17	0.13	1.96	1.06	0.03	0.07	5.59	4.76
	(0.33)	(0.02)	(0.35)	(0.10)	(0.00)	(0.01)	(0.25)	(0.25)
Yaya								
Teak								
A	4.36	0.37	11.13	1.61	0.02	0.18	8.66	6.47
	(1.60)	(0.07)	(2.30)	(0.20)	(0.01)	(0.02)	(0.75)	(0.28)
B	2.59	0.11	3.69	0.72	0.02	0.06	5.40	5.98
	(1.06)	(0.02)	(0.85)	(0.05)	(0.00)	(0.01)	(0.32)	(0.39)
Logged forest								
A	5.58	0.54	11.76	2.99	0.02	0.30	13.18	6.67
	(0.50)	(0.10)	(1.60)	(0.49)	(0.00)	(0.04)	(1.60)	(0.08)
B	1.83	0.18	1.13	0.84	0.02	0.05	5.89	4.53
	(0.34)	(0.03)	(0.30)	(0.11)	(0.00)	(0.00)	(0.21)	(0.28)

APPENDIX XVIII

ONE-WAY ANOVA COMPARING THINNED AND UNTHINNED TEAK PLANTATIONS, TAIN II.

Variable	Source	DF	SS	MS	F-ratio	Prob. F
Ca	Bg	1	5.5862	5.5862	5.7845	0.0306*
	error	14	13.5200	0.9657		
	total	15	19.1062			
K	Bg	1	0.0002	0.0002	0.0189	0.8926
	error	14	0.1543	0.0110		
	total	15	0.1545			
Mg	Bg	1	0.3717	0.3717	8.0109	0.0134*
	error	14	0.6495	0.0464		
	total	15	1.0212			
Na	Bg	1	0.0007	0.0007	0.8424	0.3743
	error	14	0.0122	0.0009		
	total	15	0.0129			
Nt	Bg	1	0.0048	0.0048	0.3304	0.5746
	error	14	0.2024	0.0145		
	total	15	0.2072			
%Om	Bg	1	4.8930	4.8930	118.9706	0.0000***
	error	14	0.5758	0.0411		
	total	15	5.4688			
P	Bg	1	0.0079	0.0079	30.6621	0.0001*
	error	14	0.0036	0.0003		
	total	15	0.0115			
pH	Bg	1	0.0051	0.0051	0.1447	0.7167
	error	6	0.2124	0.0354		
	total	7	0.2175			
% Sand	Bg	1	376.4768	376.4768	103.3662	0.0001***
	error	6	21.8530	3.6422		
	total	7	398.3298			
%Clay	Bg	1	4.6705	4.6705	10.7769	0.0168*
	error	6	2.6003	0.4334		
	total	7	7.2708			

*** = $P < 0.001$
** = $p < 0.01$
* = $p < 0.05$
Bg = Between Groups
Wn = Within Groups

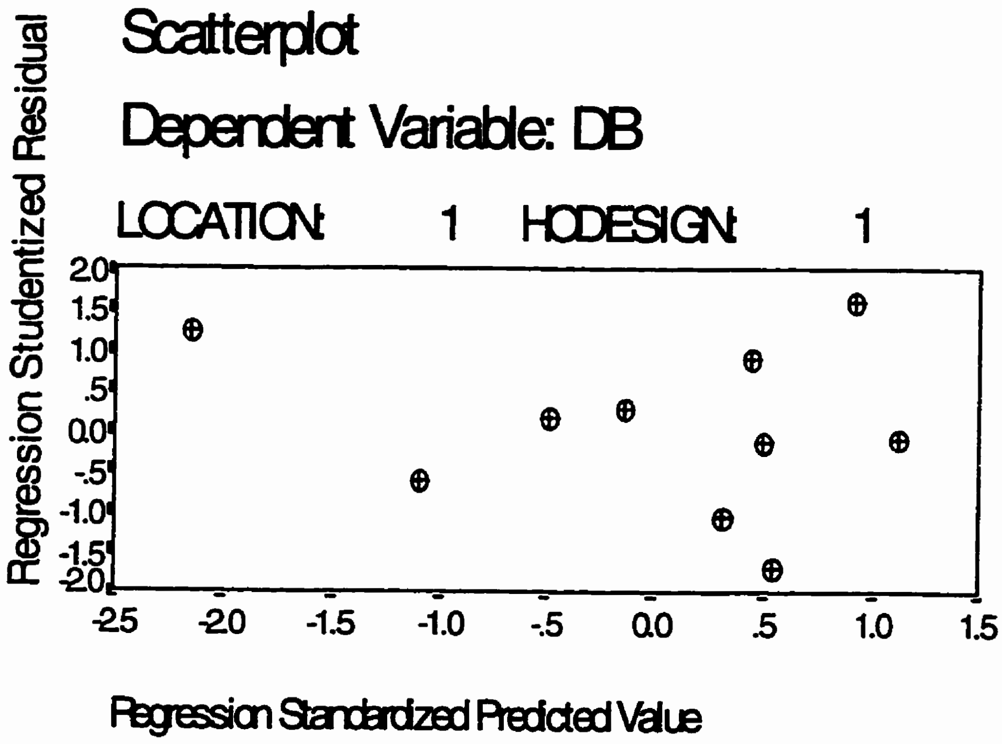
APPENDIX XIX

RESIDUAL PLOTS AND STATISTICS FOR MODEL B1, BOSOMOA.

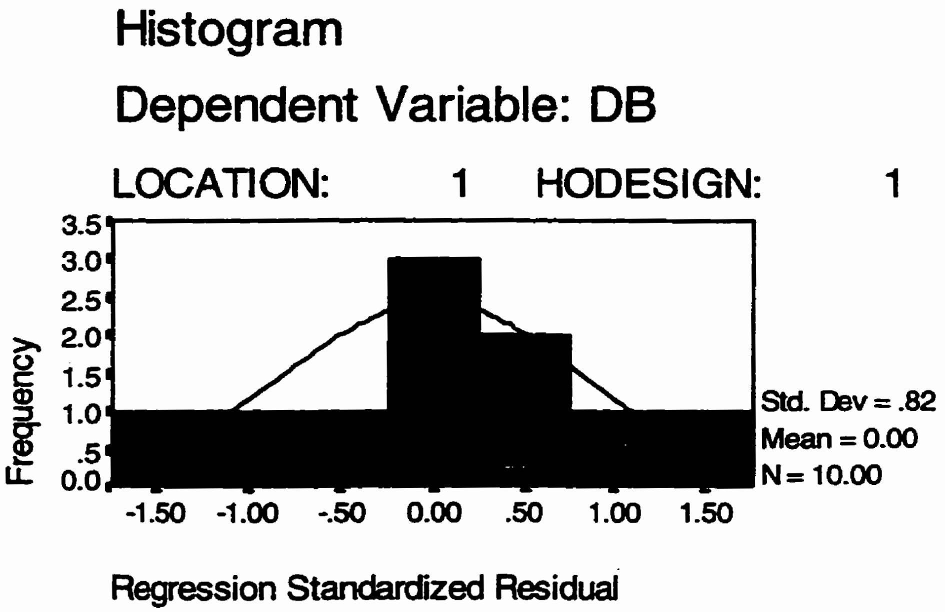
A: RESIDUAL STATISTICS.

	Min	Max	Mean	Std Dev	N
*PRED	1.0204	1.4843	1.3250	.1420	10
*ZPRED	-2.1451	1.1221	.0000	1.0000	10
*SEPRED	.0186	.0493	.0308	.0115	10
*ADJPRED	.8243	1.4866	1.3075	.1928	10
*RESID	-.0726	.0742	.0000	.0422	10
*ZRESID	-1.4045	1.4351	.0000	.8165	10
*SRESID	-1.7017	1.6083	.0639	1.0255	10
*DRESID	-.1066	.2157	.0175	.0904	10
*SDRESID	-2.1596	1.9465	.0587	1.1823	10
*MAHAL	.2661	7.2839	2.7000	2.7025	10
*COOK D	.0006	3.9606	.4799	1.2274	10
*LEVER	.0296	.8093	.3000	.3003	10

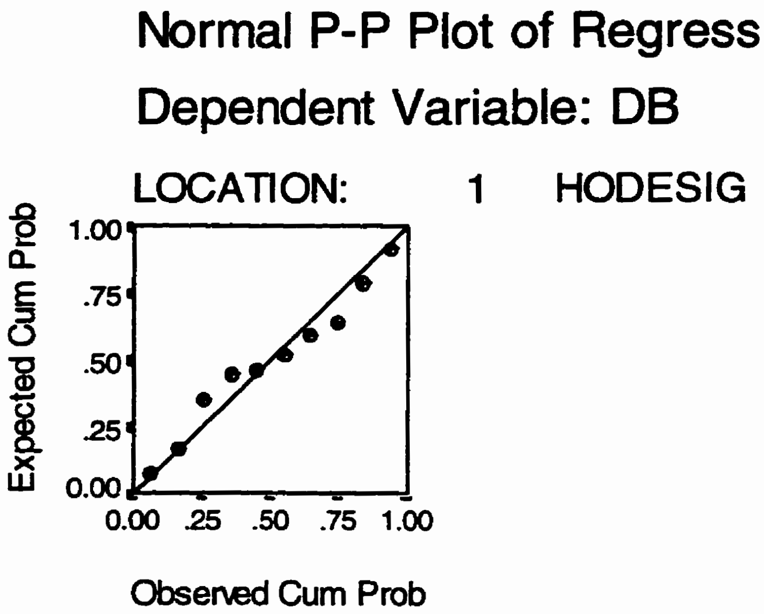
B:SCATTERPLOT OF STUDENTIZED RESIDUALS vs STANDARDIZED PREDICTED VALUES.



C : A HISTOGRAM OF REGRESSION STANDARDIZED RESIDUALS.



D: NORMAL PROBABILITY PLOT OF RESIDUALS.



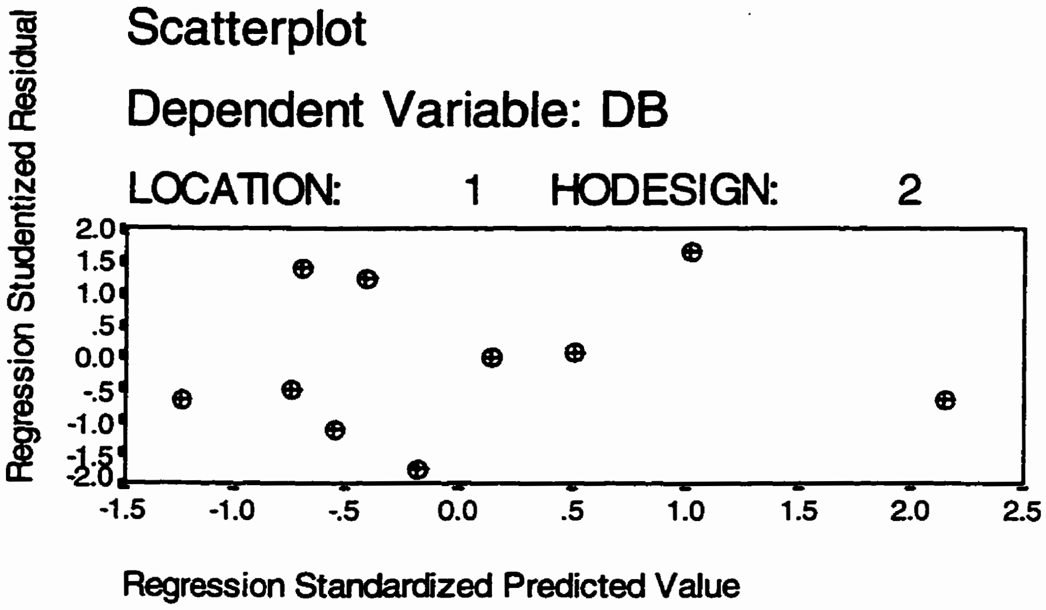
APPENDIX XX

RESIDUAL PLOTS AND STATISTICS FOR MODEL B2, BOSOMOA.

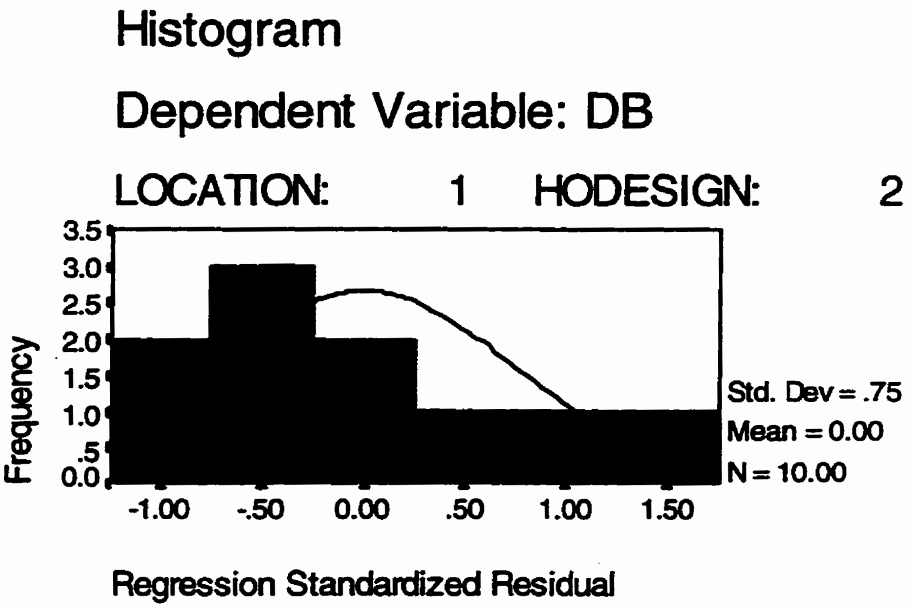
A: RESIDUAL STATISTICS.

	Min	Max	Mean	Std Dev	N
*PRED	1.3458	1.6251	1.4480	.0824	10
*ZPRED	-1.2404	2.1495	.0000	1.0000	10
*SEPRED	.0060	.0140	.0101	.0028	10
*ADJPRED	1.3565	1.6396	1.4477	.0802	10
*RESID	-.0129	.0188	.0000	.0110	10
*ZRESID	-.8699	1.2681	.0000	.7454	10
*SRESID	-1.7561	1.6630	-.0351	1.1412	10
*DRESID	-.0524	.0756	.0003	.0344	10
*SDRESID	-2.5372	2.2251	-.0207	1.4154	10
*MAHAL	.5899	7.1468	3.6000	2.2811	10
*COOK D	.0000	4.6693	.7370	1.4949	10
*LEVER	.0655	.7941	.4000	.2535	10

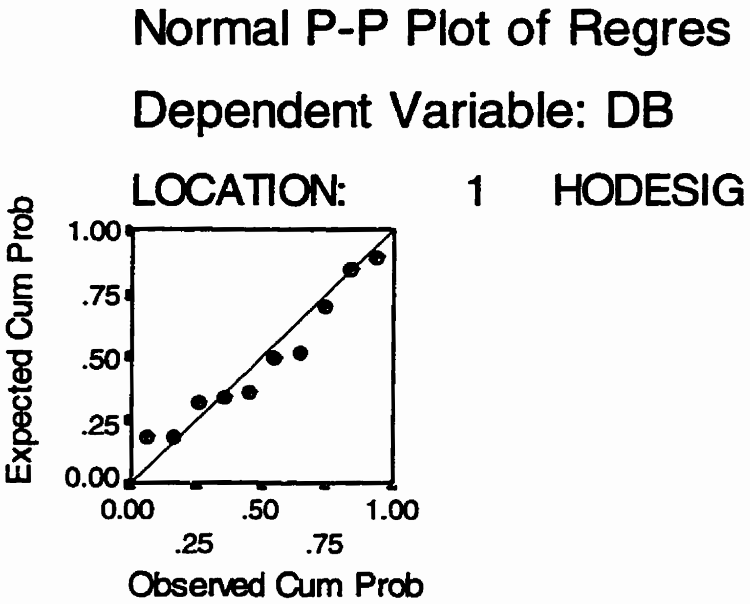
B: SCATTERPLOT OF STUDENTIZED RESIDUALS vs STANDARDIZED PREDICTED VALUES.



C: A HISTOGRAM OF REGRESSION STANDARDIZED RESIDUALS.



D: NORMAL PROBABILITY PLOT OF RESIDUALS.



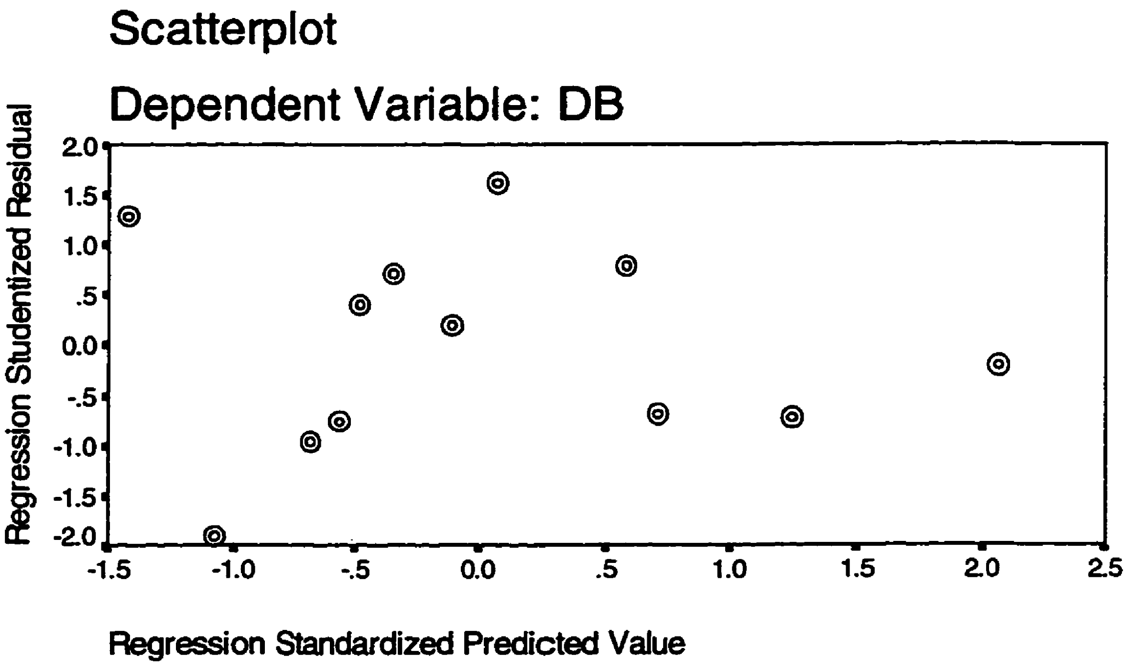
APPENDIX XXI

RESIDUAL PLOTS AND STATISTICS FOR MODEL T1, TAIN II.

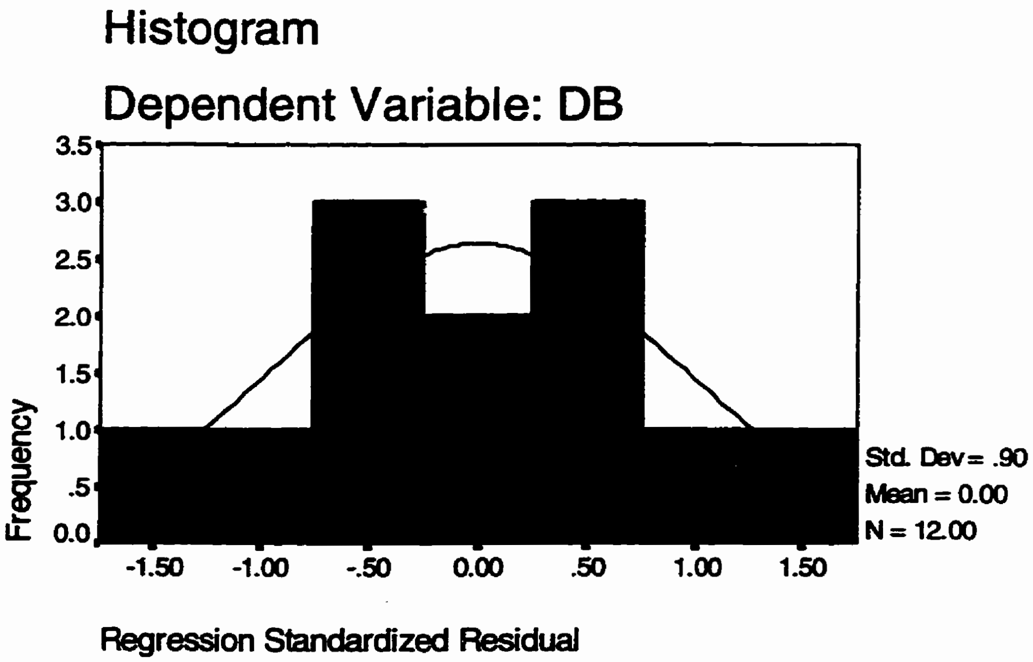
A: RESIDUAL STATISTICS.

	Min	Max	Mean	Std Dev	N
*PRED	.9165	1.6889	1.2308	.2215	12
*ZPRED	-1.4190	2.0674	.0000	1.0000	12
*SEPRED	.0363	.0853	.0596	.0172	12
*ADJPRED	.8356	1.7060	1.2357	.2349	12
*RESID	-.2020	.1916	.0000	.1118	12
*ZRESID	-1.6341	1.5495	.0000	.9045	12
*SRESID	-1.8923	1.6210	-.0172	1.0322	12
*DRESID	-.2709	.2096	-.0048	.1473	12
*SDRESID	-2.2991	1.8162	-.0295	1.1306	12
*MAHAL	.0303	4.3188	1.8333	1.5047	12
*COOK D	.0012	.4069	.1084	.1347	12
*LEVER	.0028	.3926	.1667	.1368	12

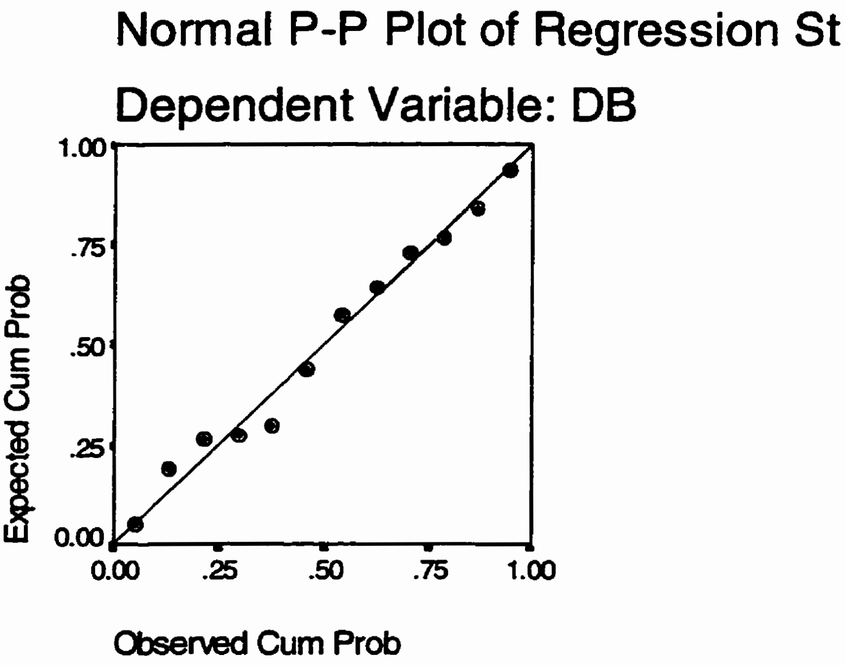
B: PLOT OF STUDENTIZED RESIDUALS vs STANDARDIZED PREDICTED VALUES.



C: A HISTOGRAM OF REGRESSION STANDARDIZED RESIDUALS .



D: NORMAL PROBABILITY PLOT OF RESIDUALS.



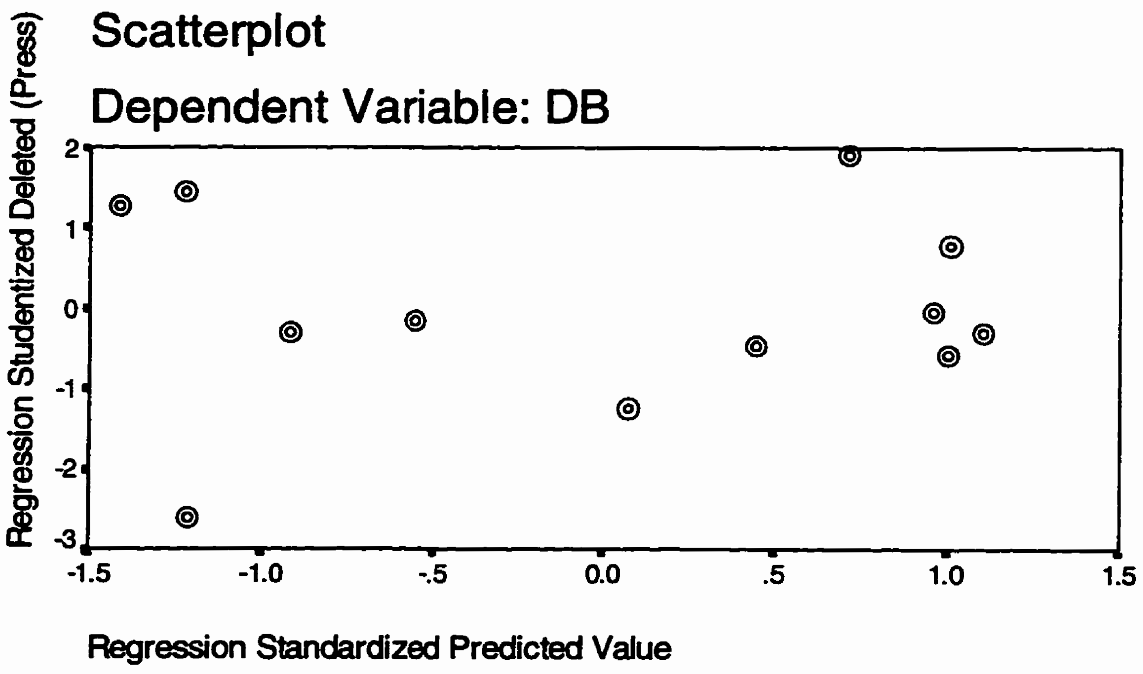
APPENDIX XXII

RESIDUAL PLOTS AND STATISTICS FOR MODEL T2, TAIN II.

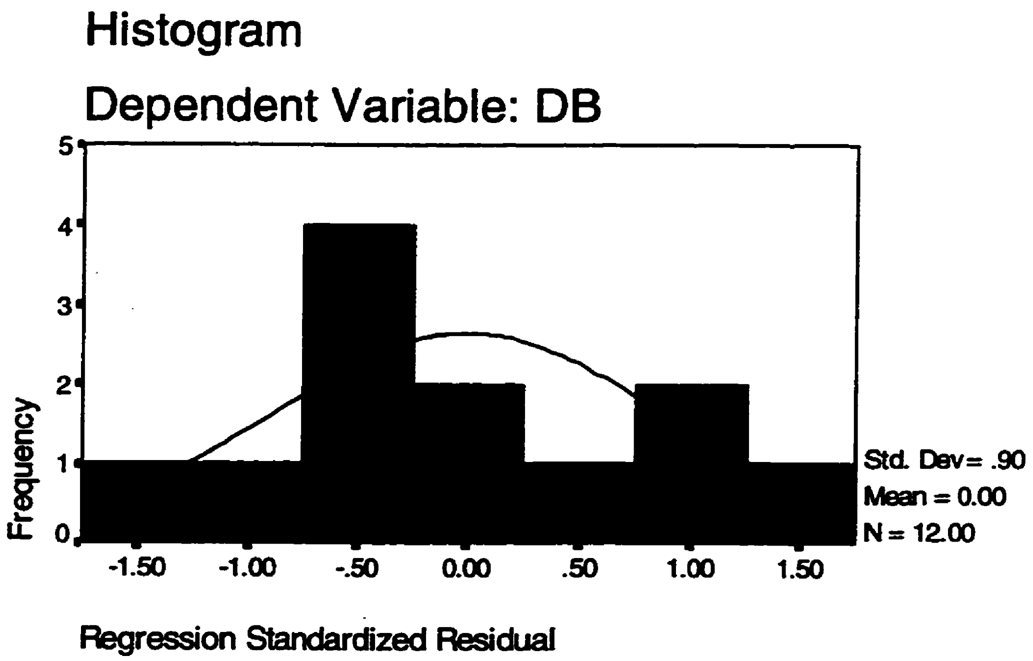
A: RESIDUAL STATISTICS

```
                   Min        Max       Mean    Std Dev    N
*PRED            .6140     1.5799     1.1550      .3835   12
*ZPRED         -1.4107     1.1078      .0000     1.0000   12
*SEPRED          .0254      .0519      .0388      .0079   12
*ADJPRED         .5664     1.5913     1.1556      .3825   12
*RESID          -.1212      .1122      .0000      .0715   12
*ZRESID        -1.5330     1.4191      .0000      .9045   12
*SRESID        -2.0312     1.6869     -.0019     1.0962   12
*DRESID         -.2128      .1586     -.0006      .1061   12
*SDRESID       -2.6023     1.9233     -.0164     1.2444   12
*MAHAL           .2180     3.8179     1.8333     1.1034   12
*COOK D          .0002     1.0392      .1825      .3007   12
*LEVER           .0198      .3471      .1667      .1003   12
```

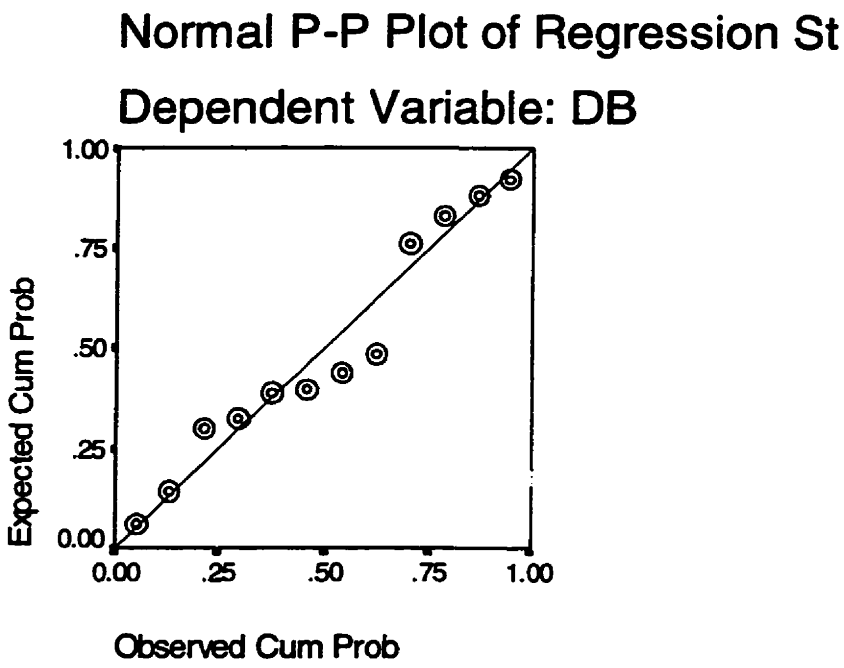
B: PLOT OF STUDENTIZED RESIDUALS vs STANDARDIZED PREDICTED VALUES.



C : A HISTOGRAM OF REGRESSION STANDARDIZED RESIDUALS.



D: NORMAL PROBABILITY PLOT OF RESIDUALS.



APPENDIX XXIII PHYSICAL PROPERTIES OF SOIL UNDER TEAK/LOGGED FOREST PAIRS .

location	Cmpt	cover type	Horizon	depth (cm)	soil matrix colour	Mechanical analysis (%) sand	silt	clay	text class	Structure[a]	Consistence[b]	Boundary[c]	Rooting[d]	Rooting depth	Db (g/cm³)	%CF	Notes
Bosomoa																	
	43	Teak	A	0-7	2.5YR4/2 weak red	87.88	10.94	1.19	S	f1gr	fr	d	vp		1.51	0.00	
			B1	7-30	5YR5/6 yellowish red	86.52	10.41	3.08	LS	m-c1sbk	fr	c	p	32	1.43	0.00	Gmelina arborea , Melicia excelsa (Odum), Anogeissus spp., Albizia ferugeni
		LogF.	A	0-12	2.5YR3/2 dusky red	89.82	6.81	3.37	S	*	l	a	p		1.33	0.00	Gmelina arborea,
			B1	12-32	2.5YR3/4 dark redish brown	92.83	3.37	3.80	S	*	l	a	f	30	1.52	0.00	
	67	Teak	A	0-13	5YR4/6 yellowish red	79.01	14.37	6.62	LS	m1sbk	fr	g	f		1.24	0.00	Emperiata cylindrica
			B1	13-44	5YR5/6 yellowish red	75.55	17.24	7.22	SL	m-c1sbk	fi-fr	a	vf	50	1.42	0.00	
		LogF.	A	0-10	5YR3/3 dark redish brown	69.95	24.59	5.47	SL	f-m1gr	fr	g	f-p		1.22	0.00	
			B1	10-32	10YR5/3 brown	65.44	26.5	8.06	SL	f-c1sbk	fr	g	f	32	1.30	0.00	
	68	Teak	A	0-15	2.5YR3/4 dark redish brown	80.67	11.59	7.75	LS	f-csbk	vfr	d	p		1.38	0.00	Gmelina arborea, Daniela oliveri,
			B1	15-45	2.5YR4/6 red	76.53	13.42	10.06	SL	f-csbk	fr	d	f	45	1.53	0.00	Emperiata cylindrica, Anogeissus spp.,
		LogF.	A	0-30	2.5YR3/4 dark redish brown	82.08	10.60	7.33	LS	f-m1sbk	fr	d	vp		1.12	0.00	Gmelina arborea
			B1	30-100	7.5YR4/4 black to dark brown	82.34	11.00	6.67	LS	c1sbk	fr	c	f	100	1.34	0.00	
	83	Teak	A	0-7	2.5YR3/6 dark red	70.72	17.94	11.35	SL	f2gr	fr	di	p		1.15	0.00	Gmelina arborea, Anogeissus spp
			B1	7-30	2.5YR4/6 red	70.60	12.93	16.48	SL	m2sbk	fr	di	f	30	1.48	0.00	
		LogF	A	0-20	2.5YR3/4 dark redish brown	79.27	14.42	6.32	LS	f2-3gr	fr	g	p		1.46	0.00	Gmelina arborea, Anogeissus spp. albizia spp
			B1	20-50	2.5YR4/6 red	77.45	10.27	12.28	SL	m-c1sbk	fr	di	p	50	1.45	0.00	
	108	Teak	A	0-13	5YR4/6 yellowish red	84.88	12.30	2.93	LS	f1*	fr	g	vp		1.36	0.00	Gmelina arborea, Anogeissus spp
			B1	13-80	5YR5/6 yellowish red	81.15	14.37	4.49	LS	f-m1sbk	fr	c	p	80	1.40	0.00	Daniela oliveri, Borasus palm
		LogF	A	0-18	2.5YR3/3 dark redish brown	80.01	15.81	4.19	LS	f1*	fr	g	vp		1.31	0.00	Borassus palm, Gmelina arborea,
			B1	18-45	5YR5/6 yellowish red	79.54	16.03	4.44	LS	f-m1sbk	fr	c	f	45	1.48	0.00	Triplochiton scleroxylon
Tanil	146	Teak	A	0-20	5YR3/4 dark redish brown	53.19	33.40	13.42	SL	f-m2gr	fr	di	f	48	1.38	19.00	Chromolina udorata, Antiaris africana,
			B1	20-48	2.5YR4/4 redish brown	50.31	27.72	21.98	SCL	m-c2-3gr	fi	c	f		1.11	72.25	Afzelia africana
		LogF.	A	0-20	5YR3/4 dark redish brown	53.89	35.79	10.33	SL	f-m2gr	fr	c	p	48	1.29	0.00	
			B1	20-48	2.5YR4/4 redish brown	58.16	24.02	17.83	SL	m2gr	fr	c	vp		0.86	81.25	
	147	Teak	A	0-10	2.5YR3/2 dusky red	42.88	40.56	16.57	L	f-m2gr	fr	di	f	35	1.23	21.50	Melicia excelsa (Odum), Ceiba pentandra
			B1	10-35	2.5YR4/4 redish brown	44.99	31.69	23.32	L	m-c2-3gr	fi	c	f		0.74	81.75	(Oyina), Pycnanthus angolensis (Otie), Chromolina odorata,
		LogF	A	0-18	2.5YR3/2 dusky red	56.39	34.10	9.51	SL	f-m2gr	fr	c	p	40	1.25	0.00	Celtis zenkeri, Albezia feregina,
			B1	18-40	2.5YR3/4 dark redish brown	57.47	25.50	17.03	SL	m2gr	fr	c	vp		0.64	74.75	Mesopogodonia perpeferifera Chromolina odorata
	160	Teak	A	0-16	5YR3/2 dark redish brown	45.43	36.78	17.80	L	f-m2gr	fr	di	f	40	1.00	23.75	
			B1	16-40	2.5YR3/6 dark red	43.29	26.86	29.85	CL	m-c2-3gr	fi	c	f		0.68	80.75	
		LogF.	A	0-10	5YR4/4 redish brown	41.79	37.94	20.28	L	f-m2gr	fr	c	p	31	1.14	23.00	Chromolina odornta, Mansonia spp.,
			B1	10-31	2.5YR4/6 red	39.81	35.07	25.12	L	m2gr	fr	c	vp		1.47	16.50	Tetrapleura tetraptera (Prekese)
	242	Teak	A	0-20	5YR3/2 dark redish brown	47.38	42.87	9.76	L	f-m2gr	fr	di	f	44	1.31	0.00	Ceiba pentandra, Kyenkyen Terminalia
			B1	20-44	5YR4/2 dark redish grey	45.14	36.69	18.18	L	m-c2-3gr	fi	c	f		1.35	14.25	ivorensis, Melicia excelsa (Odum)
		LogF.	A	0-20	2.5YR3/4 dark redish brown	50.22	33.25	16.54	L	f-m2gr	fr	c	p	48	1.09	4.25	Melicia excelsa , Albezia zygia (Okoro),
			B1	20-48	2.5YR3/6 dark red	64.90	20.87	14.24	SL	m2gr	fr	c	vp		0.50	78.00	Chromolina odorata,
	200	Teak	A	0-20	2.5YR3/4 dark redish brown	35.16	45.02	19.83	L	f-m2gr	fr	di	f	50	1.56	0.00	Pycnanthus angolensis, Melicia excelsa,
			B1	20-50	5YR4/6 yellowish red	28.36	32.96	38.69	CL	m-c2-3gr	fi	c	f		1.55	21.50	Ceiba pentandra Chromolina odorata
		LogF.	A	0-12	2.5YR3/4 dark redish brown	42.90	44.71	12.40	L	f-m2gr	fr	c	p	22	1.37	0.00	
			B1	12-22	5YR4/6 yellowish red	33.19	40.80	26.02	CL	m2gr	fr	c	vp		1.47	52.00	
	300	Teak	A	0-25	2.5YR3/4 dark redish brown	62.20	29.42	8.36	SL	f-m2gr	fr	di	f	50	0.92	0.00	Cola gigantea (Wawatapuo), Trichilia
			B1	25-50	2.5YR4/4 redish brown	54.07	34.09	11.85	SL	m-c2-3gr	fi	c	f		1.51	0.00	prieureana, Ceibapentandra, Chromolina odorata
		LogF.	A	0-20	2.5YR3/4 dark redish brown	50.34	39.41	9.26	SL	f-m2gr	fr	c	p	40	1.09	0.00	
			B1	20-40	2.5YR4/8 red	44.87	39.43	15.71	L	m2gr	fr	c	vp		1.30	27.50	
Yaya	28	teak	A	0-15	2.5YR3/4 dark redish brown	71.08	19.80	9.13	SL	f3gr	fr	c	vp		1.31	7.75	Cola gigantea, Ceiba pentandra
			B1	15-45	2.5YR4/4 redish brown	69.55	14.11	16.35	SL	f-m1sbk	m	di	f-p	45	0.89	26.00	
		LogF	A	0-30	2.5YR3/4 dark redish brown	66.70	24.63	8.68	SL	f-m3gr	fr	g	vp		1.37	0.00	Trichilia prieureana, Amphimas
			B1	30 +	2.5YR4/6 red	55.37	17.74	27.00	SCL	f-m1sbk	fi	c	f	30	1.60	14.75	pterocarpoides (Yaya), Melicia excelsa, Terminaliar superba (Ofram) Pycnanthus angolensis (Otie)
	33	Teak	A	0-10	5YR3/4 dark redish brown	61.68	23.89	14.43	SL	f-m2-3gr	fr	di	f		1.01	6.00	Amphimas pterocarpoides (Yaya), Cola
			B1	10-43	5YR4/6 yellowish red	63.69	16.85	19.47	SL	m-c3gr-sbk	fi	di	vf	43	1.02	52.75	gigantea (Wawatapuo), chromolina odorata
		LogF.	A	0-12	5YR4/3 redish brown	50.52	31.32	18.17	L	f-m3gr	vfr	di	vp		0.96	0.00	
			B1	12-40	5YR4/6 yellow red	58.59	17.07	24.34	SCL	m-c3sbk	vfr	c	f	40	1.45	36.75	
	34	Teak	A	0-9	2.5YR3/2 dusky red	70.47	20.07	9.47	SL	f-m2gr	fr	di	f		1.00	28.25	Triplochiton scleroxylon, Tetrapleura
			B1	9-25	5YR4/4 redish brown	68.22	14.26	17.53	SL	m-c2-3gr	fi	c	f	25	0.93	69.25	tetraptera, Morus mesozygia (Wonton) Celtis spp.
		LogF.	A	0-10	2.5YR3/4 dark redishbrown	73.73	17.12	9.16	SL	f-m2gr	fr	c	p		1.38	0.00	Pycnanthus angolensis (Otie), Pawpaw
			B1	10-43	5YR4/6 yellowish red	63.47	15.06	21.48	SCL	m2gr	fr	c	vp	43	1.17	32.00	

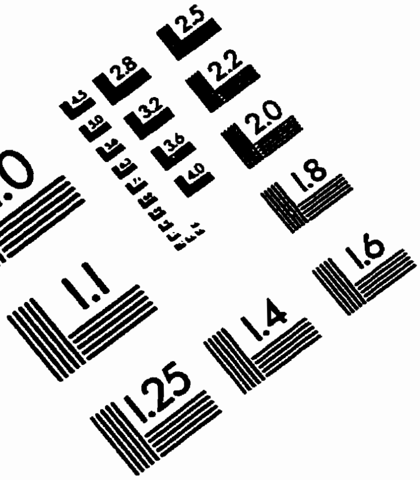
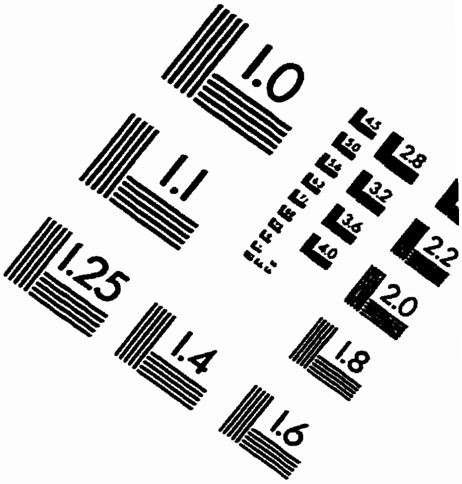
[a] c = coarse, m = medium, f = fine; 1 = weak, 2 = moderate, 3 = strong; gr = granular, sbk =subangular blocky, * = structureless

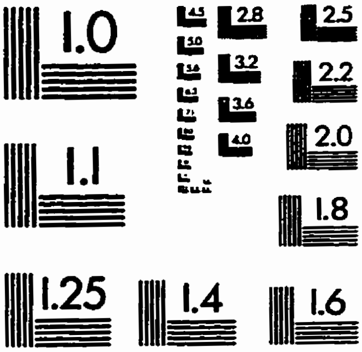
[b] d = dry, fi = firm, fr = friable, vfr = very friable, m = moist, l = loose

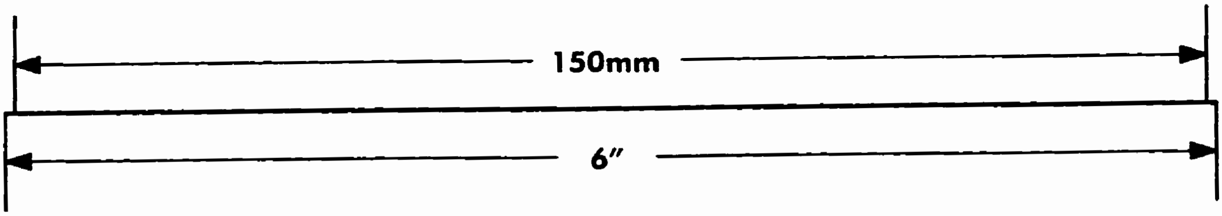
[c] d = diffuse, a = abrupt, c = clear, g =gradual , di = distinct

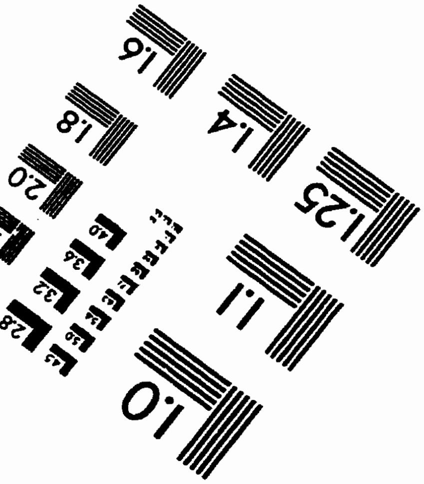
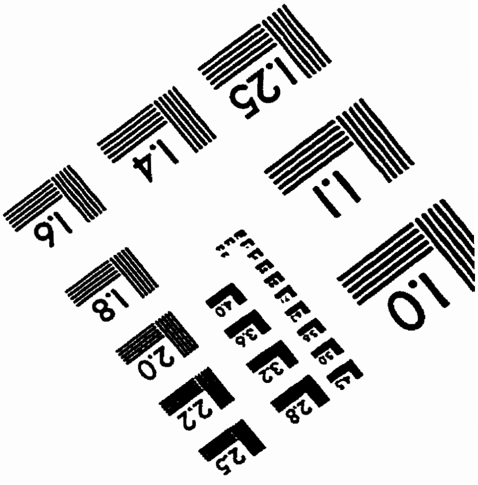
[d] v = very, f = few, m = moderate, , p = plentiful

IMAGE EVALUATION
TEST TARGET (QA-3)





APPLIED IMAGE . Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989