SOIL CHARACTERIZATION FOR TEAK (*TECTONA GRANDIS*) PLANTATIONS IN NZARA DISTRICT OF SOUTH SUDAN

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DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work under the supervision of Doctor Andrei Rozanov and Professor Paxie Chirwa, that I am the owner of the copyright thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: 18 June 2008

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ABSTRACT

The characterization of soils in Nzara District of Southern Sudan in comparison to other tropical teak growing countries (*Tectona grandis*) – in respect of extensions to existing and/or the establishment of new teak plantations – were done by firstly considering the soils of three existing plantations: Yoboa, Mabarizinga and Nagondi, and secondly by considering soils outside and inside the existing teak plantations in respect of land uses. From these soil characterizations, it emerged that considerable positive returns can be expected from teak plantings in the area as an investment, provided that appropriate site management is implemented.

Climatic data of the Nzara area compared favorably with the climatic range of areas where teak grows naturally and the world's dominant producers: mean annual rainfall 1350-1600 mm with a distribution over 6-8 months compares well with that of Myanmar (1250-3750 mm) and Indonesia (1511-2108 mm) both with at least 3 months of dry season. The mean annual temperature of 28-35^{0}C compares well with 15-41^{0}C and 30-32^{0}C of Myanmar and Indonesia respectively.

The Yoboa and Mabarizinga sites should be prioritized as they appear slightly more suitable than the Nagondi site. All three sites have a dominant soil texture of Sandy Clay Loam similar to Sandy Loam of most areas of other tropical countries where teak is growing well (such as India, Indonesia and Nigeria). Yoboa and Mabarizinga however distinguish themselves by having the highest soil pH_{water} values range from 6.4±0.56 and 6.04±0.7 in top soils; 5.91±0.5 and 5.46±0.61 in subsoils at Yoboa and Mabarizinga respectively; the highest soil organic matter content 1.8±0.34% and 1.92±0.43% in topsoil 0.89±0.16% and 1.13±0.19% in subsoils; as well as the highest P content in both available (0.09±0.04% and 0.03±0.04% for topsoils) and total forms (1.19±0.26% and 0.9±0.3% also on topsoils). These values though very low in absolute terms, are not much different from those of other tropical teak-growing countries. Management strategies intended to preserve and improve the present status, particularly the protection of top soil horizons against mainly water erosion, would be able to boost the site productivity.

The soils outside existing teak plantations appear less degraded and slightly more fertile compared to those inside the plantations. The slightly higher fertility of these soils outside teak plantations ought to be considered in the forester's decision to avoid conflicts that might arise with local communities who might see their lands being commissioned by forestry when the fallow period reaches its end.

SAMEVATTING

Ten einde ‘n vergelyking met ander tropiese kiaat (*Tectona grandis)* groeiende lande te tref, is ‘n ruimtelik geografiese analise van gronde by Yoboa, Mabarizinga en Nagondi, in die Nzara distrik van Suidelike Sudan gedoen. ‘n Tweede veranderlike nl. y, is vasgestel om ‘n vergelyking tussen gronde binne en buite die bestaande kiaat aanplantings vir alternatiewe gebruik toe te pas. Vanuit hierdie grondkarakteristieke het dit geblyk dat noemenswaardige positiewe omsette uit beleggings gegenereer sal word, mits die nodige area bestuur toegepas word.

Klimatologiese data van die Nzara gebiede dui daarop dat die gebied gunstig binne perke van natuurlike kiaat areas, asook die van wêreld dominant kommersiële kiaat produsente val. Die gemiddelde jaarlikse reënval van 1350-1600mm, met ‘n verspreidings-periode oor 6-8 maande, vergelyk good met Myanmar (1250-3750mm) en Indonesië (1511-2108mm), beide met ten minste 3 maande droë seisoen. Gemiddelde jaarlikse temperature van 28-35 ˚C in Nzara vergelyk met 15-41 ˚C en 30-32 ˚C vir Myanmar en Indonesië onderskeidelik.

Yoboa en Mabarizinga toon ‘n geringe beter geskiktheid bo Nagondi en behoort daarom prioriteit te geniet. Al drie areas beskik oor ‘n dominante sandkleileem grond tekstuur, soortgelyk aan sandleem tekstuur van die meeste tropiese gebiede, soos Indië, Indonesië en Nigerië, waar kiaat groei. Yoboa en Mabarizinga beskik egter oor die hoogste grond pH, wat onderskeidelik wissel van 6.4±0.56 en 6.04±0.7 in bo- en 5.91±0.5 en 5.46±0.61 in ondergronde, hoogste organiese fraksie van 1.8±0.34% en 1.92±0.43% in bo- en 0.89±0.16% en 1.13±0.19% in ondergronde asook die hoogste beskikbare- (0.09±0.04% en 0.03±0.04%) en totale stikstof (1.19±0.26% en 0.9±0.3%) in bo-gronde. Alhoewel hierdie waardes laag is in absolute terme, is hul tog vergelykend tot die van ander tropiese kiaat produserdende lande. Daadwerklike bestuursinsette moet egter geneem word ten einde hoofsaaklik watergedrewe erosie van bogrond horisonte te bekamp en die huidige toestand van gronde te verbeter en te bewaar. Sodanige praktyke kan produksie noemenswaardig verhoog.

Gronde buite kiaat aanplantings het minder verspoel en het ’n effens hoër grondvrugbarheid getoon in vergelyking met die aanplantings binne. Hierdie hoër vrugbaarheid buite plantasies moet voldoende aandag geniet in die besluitneming van bosbouers ten einde moontlike konflik met gemeenskapsbelange te vermy, wanneer voorafbepaalde braak-tydperke verstrek.

ABSTRAIT

La caractérisation des sols du district de Nazara au Sud Soudan, en comparaison avec ceux d'autre pays tropicaux plantant le teck (*Tectona grandis*), à des fins d'extension et/ou d'établissement de nouvelles plantations a été faite en séparant dans un premier temps les échantillons de sol en fonction de leur origine géographique entre trois sites : Yoboa, Mabarizinga and Nagondi. Une seconde comparaison a été faite entre les échantillons provenant de l'intérieur ou de l'extérieur des plantations du teck existantes. Les sols à l'extérieur des plantations existantes sont considérés comme identiques à ceux existants sur les terres agricoles en jachère. Cette caractérisation des sols montre qu'un tel investissement peut procurer de considérables gains positifs aussi bien sociaux qu'économiques, à condition qu'ils soeint accompagnés de nombre de mesures d'aménagement des sols.

En effet, les conditions climatiques dans les environs de Nzara sont dans les mêmes gammes que celles d'autres zones tropicales où le teck pousse naturellement, et des pays dominant le marché mondial de sa production : moyenne pluviométrique annuelle 1350-1600 mm à Nzara avec 6 à 8 mois de saison sèche, en comparaison avec par exemple le Myanmar (1250-3750 mm) d'où le teck est originaire, ou l'Indonésie (1511-2108 mm), le plus grand producteur du teck au monde, tout deux avec au moins trois mois de saison sèche ; température moyenne annuelle 28-35° C, à comparer avec 15-41°C et 30-32°C au Myanmar et en Indonésie respectivement.

La partie plus au Sud de la zone, où se localisent les plantations existantes du site de Yoboa, suivi par celui de Mabarizinga, doivent être prioritaires du fait qu'ils apparaissent légèrement plus appropriés pour le teck que la partie plus au Nord du secteur d'étude (site de Nagondi). Les trois sites ont un sol à texture dominante de type Sableux-Argileux-Loam, similaire à celle de la plupart des sols d'autre pays tropicaux sur lesquelles le teck est planté, comme l'Inde, l'Indonésie ou le Nigeria. Les sols des sites de Yoboa et Mabarizinga se démarquent par leur propriétés chimiques et leurs taux élevés en éléments nutritifs majeur : pH_{H20} respectivement entre 6.4±0.56 et 6.04±0.7 au niveau des horizons supérieurs et 5.91±0.5 et 5.46±0.61 dans les horizons profonds à Yoboa et Mabarizinga; taux de carbone organique de l'ordre de 1.8±0.34% et 1.92±0.43% dans les horizons supérieurs et 0.89±0.16% et 1.13±0.19% dans les horizons de profondeur ; leurs taux de phosphore disponible (0.09±0.04% et 0.03±0.04% dans les horizons supérieurs) et phosphore total (1.19±0.26% et 0.9±0.3% dans les horizons supérieurs) sont les plus élevés de ceux mesurés dans cette étude. Ces valeurs, bien que faibles, ne sont pas très éloignées de celles relevées dans les sols des autre pays tropicaux producteurs de teck. De considérables efforts de management visant à conserver et à améliorer les horizons supérieurs, en particulier la lutte contre l'érosion de l'eau, sont susceptibles de largement améliorer leur état et d'élever la productivité. Les sols a l'extérieur des plantations de teck apparaissent moins dégradés et légèrement plus fertiles que ceux à l'intérieur. En effet ils possèdent une texture dominante de type Sableux-Argileux-Loam et des taux élevés d'éléments majeurs nutritifs : leur pHs, carbone organique, phosphore disponible et total sont les plus élevés de ceux mesurés dans cette étude. Un tel différence de fertilité entre les sols plantés ou non, aussi légère soit-elle, implique une attention particulière lors des décisions finales d'établissement de plantations de teck, pour éviter un conflit avec les populations locales voyant à travers une telle opération une confiscation de leur terres laissées en jachère.

DEDICATION

I dedicate this Master thesis to my late grand father the village chief Vital Ebamangoy with whom I spent my childhood and become acquainted with the management of tropical rainforest through the practice of slash and burn agriculture in the Haut-Ogoue-Gabon; and to the Roman Catholic Claretaines Missionaries Nuns, particularly to Sister Odeth Bueno and Sister Sylva Thereza, who have supported and encouraged me in my studies through towns to cities back home in Gabon.

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PREFACE

Being the second child of a family of 12 children in a Third World country and having had the opportunity of governmental financial support to study abroad, there were no excuses but to succeed in the hope of making a contribution to the improvement of the everyday struggle in the tropics. Far from my personal experience of struggling to get where I am today: I believe and agree with the former South African president Mr. Nelson Mandela that "Education is the great engine to personal development. For it is through education that the daughter of a peasant can become a doctor, that the child of a farm worker can become the president of a great nation. That it is what we make of what we have, not what we are given, that separates one person from another." My wish and great hope is that my achievement serves as a motivation for my younger brothers and sisters; for them to believe in what they have and embrace the few opportunities they may meet on their ways.

PRÉFACE

Etant le deuxième né d'une famille de 12 enfants dans un pays du Tiers Monde, et avoir eu l'opportunité de bénéficier d'une bourse gouvernementale pour étudier a l'étranger, l'échec n'aurait eu aucune excuse et aucune autre alternative que la réussite ne donne l'espoir d'être capable d'apporter ma contribution à l'amélioration de la vie quotidienne que l'on vit sous les tropiques. Mon itinéraire personnel et le chemin parcouru jusqu'au diplôme de Master en Science de la Forêt, me font croire et partager avec l'ancien président Sud-Africain Monsieur Nelson Mandela la conviction que « l'Education est le plus grand moteur du développement personnel. Grâce à l'éducation, la fille d'un paysan peut devenir un docteur, le fils d'un ouvrier de ferme peut devenir président d'une grande nation. C'est ce que nous avons au profond de nous, et non pas ce qui nous est donné, qui sépare une personne d'une autre. ». Je souhaite, et je crois que ce que j'ai accompli soit un exemple pour mes cadets, afin qu'ils croient au potentiel qu'ils ont individuellement et saisissent le peu d'opportunités qu'ils croiseront sur leurs route.

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INTRODUCTION

Plantation forestry forms an important alternative means of wood production in the tropics and has been practiced for long time throughout the tropical countries since the colonial period by the expansion of forest plantations. However, the productivity at many of these sites is generally below their potential. Nevertheless, opportunities exist for increasing wood production by adopting appropriate soil and management practices (Mallapureddi, 2002).

Many tropical forest hard wood tree species are in high demand by the timber trade but, with a few notable exceptions such as teak (*Tectona grandis*), they are difficult to grow in plantations, Raymond (1996). According to Evans and Turnbull (2004), tropical hardwood forests are so variable, non-uniform, and difficult to ecologically manage that foresters generally prefer to use exotic species that are more uniform, easier to handle, and whose products are known and accepted. As Evans and Turnbull (2004) commented, even though some of the tropical hardwoods have magnificent wood and mostly desired species they are slow growing and hard to manage in plantations. Furthermore, current knowledge about how these tropical hard wood tree species should be handled is generally insufficient. Thus, foresters are often trained to handle the exotic species and feel comfortable with them. Evans and Turnbull (2004) concluded that because exotic tree species grow at a rapid rate, they are commonly chosen as the heart of an economically viable forestry enterprise in tropical areas.

Despite the fact that this species, *Tectona grandis*, was introduced in some tropical countries some 100 years ago such as Ghana in 1905; Trinidad in 1913, Côte d'Ivoire in 1929, in addition to the world's continuously increasing demand for teak, the current supply is far below the need of the market in comparison to other hard wood species such as Eucalypt and Acacia, (Pérez and Kanninen, 2005).

The limiting factors explaining the current lower supply of teak from tropical countries are multiple among others are the species suitability related to the edaphic factors and the land availability for plantations. While the edaphic factors are dictated by nature and have often been improved through different land management practices, the availability of land imposed by human settling is often the most limiting factor faced by forestry agencies. The principal reason is simply the fact that the best lands are allocated for crop production rather than to tree plantations. Thus, forest plantations are usually established on marginal lands unsuitable for agriculture crops. In this manner, the usually immediate or delayed conflict between local people and the forestry agencies and/or political government is avoided. A thorough investigation of soils and other edaphic factors is therefore crucial for land suitability evaluation and delineation of boundaries.

The aforestation potential of Southern Sudan has been recognized since colonial times and this has resulted in the creation of natural reserves and the establishment of some teak plantations around certain towns such as Yambio, Katire. Though the current productivity results are far behind what could have been expected, there are still some good reasons to believe that some improvements can be made for future plantations. Moreover, despite the fact that the toll in suffering, lack of developmental progress, damage to vital infrastructures and natural resources degradation caused by the armed conflict affects the whole country, it is disproportionately much more severe in the Southern Sudan (USAID, 2003/2004). High value timber such as teak will contribute to enhance the economic stature of the region through among others job opportunities and social support. However, the same ongoing political conflict in the country since its independence which has forced millions of local people to leave their land remains a critical issue that needs to be thoroughly considered before any further establishment of plantations is attempted on fallow land.

This thesis aims to investigate whether substantial differences exist between soils of three sites: Nagondi, Yoboa and Mabarizinga and furthermore under two major different land uses: the current teak plantations and the fallow lands of different ages with diversified vegetation cover. The thesis is divided into two main parts:

The allocation of forest plantations or any other type of land uses on an area requires preliminary studies of soil and environmental suitability. The first part of this thesis therefore investigates whether the current teak plantations of South Sudan did meet the soil and environmental requirements when they were established on the area. Completely lacking recorded data from the time these plantations were established some 60 years ago, the investigation of soil and environmental suitability of teak on the current three sites (Nagondi, Yoboa and Mabarizinga) can only be undertaken by comparing these sites soils and edaphic factors with those of countries were teak is indigenous such as the Laos Republic and countries dominating the world market of the species such as Indonesia. The outcomes of these investigations aim at formulating recommendation for the establishment of new teak plantations or an extension of the current ones.

A Forest plantation as a land use is often perceived as susceptible to soil degradation. It is often assigned to areas with low food crop value such as land on steep slopes. In a situation where forest plantations have been standing side by side with the main agriculture system of the tropic such as shifting cultivation, it is a golden opportunity to investigate the impact of both land uses on particularly physical and chemical soil attributes. The outcomes of such an investigation might change the perception towards forest plantation, especially of local people and private investors who should then see forest plantations as a valuable land use alternative. The second part of this thesis will consider the physical and chemical attributes of soil sampled inside the teak plantations and compare them with their counterpart outside of these plantation considered to be shifting cultivation lands on fallow of different ages.

In the light of the above outcomes and with the help of satellite images analysis and interpretation, estimations can be made on the proportion of available lands suitable for the establishment of new teak plantations, avoiding as possible the use of more potential lands for agricultural crops and currently under different ages of fallows.

Finally, recommendations on land management prior to planting and silvicultural practices at planting and during the rotation length of the plantation stand will be formulated for establishing new teak plantations.

I. LITERATURE REVIEW

This chapter aims to present teak, its place in the world timber market and its growth requirements (edaphic factors) from the indigenous habitats to the established forest plantations throughout the world. It also introduces the Nzara Southern Sudan study area: its potential for forest plantations recognized long ago and the current state of the existing teak plantations in the area compared to other tropical countries growing teak on plantations.

1. Teak: Presentation and Biological Description

Teak, *Tectona grandis* of the family of Verbenaceae (**Fig. 1**), is one of the best known and most valuable tropical hard woods in the world (Raymond, 1996). It is a large broad-leafed and deciduous tree that shades its leaves during the dry season as litter fall including branches, twigs and bark. Teak is a cross pollinating species even though monoecious, that is with pistils and anthers being carried on the same flower. Occasionally, self-pollination occurs but germination is said to be poor (Raymond, 1996). The tree ranges from 30 meters in height with a girth over one meter on good sites to 12 meters in height on poor sites (Zanin, 2005).

Figure 1. ***Young teak tree in Eastern Java Indonesia plantation (Moh. Na'iem, 2005). Here is seen the pair disposition of broadleaves and the straightness of the stem.***

This important tropical timber species only occurs naturally in South East Asia: parts of India, Myanmar, Lao People's Democratic Republic (Laos), and Thailand (Purwanto and Tokuchi, 2005). However, it has been naturalized in Java: Indonesia where it is thought to have been introduced some 400 to 600 years ago and which is currently the country leader of teak logs production. Many other teak plantations have also been established worldwide in the tropics: Africa (including Côte d'Ivoire, Nigeria, Sierra Leone, and The United Republic of Tanzania Benín and Togo), Latín America and the Caribbean (Costa Rica, Colombia, Ecuador, El Salvador, Panama, Trinidad, Tobago and Venezuela). Teak has also been introduced in some islands in the Pacific region (Papua New Guinea, Fiji and Solomon Islands) and in northern Australia at trial levels (Pandey and Brown, 2002).

2. Wood Quality and Use

Timber wood strength is correlated with wood density. Therefore, heavier timbers have greater strength. According to Zanin (2005), what makes teak so special is that it is a strong timber given its light weight. The value of teak wood quality was recognized centuries ago and this is reflected by its genus name "Tectona" which is a Greek word *tekton*, meaning "carpenter"; and for long it has been qualified and considered as the "carpenter's pride" (Bhat and Hwan, 2007). Such a qualification is related to a number of distinctive attributes that differentiate teak wood from that of other genus hard woods. Indeed, beside its wood strength and lighter weight, it is admired for its straight grain and ease of use (**Fig. 2**). Furthermore, it has a high aesthetic value and is used to produce flooring, lumber for shipbuilding, interior and exterior furniture, musical instruments, and containers for corrosive chemicals since it does not cause corrosion when in contact with metal and general carpentry.

Perhaps the most important aspect of teak wood is its durability, pests and diseases resistibility particularly under tropical areas prone to many diseases and pests. Zanin (2005), reports that Teak has been known to last over 700 years in dry climate and decades in humid environments while in contact with the ground; and that it is resistant to most pests and fungi. It is however recognized not to be a good source of household energy as its burning emits excessive smoke. *Tectona grandis*' strength, straightness, workability and resistance to many pests and diseases have made it a standard which is used to rank and compare other timbers. As the German forester Dietrich Brandis stated (ITTO, 1990) some 150 years ago "Among timbers, teak holds the place which diamond maintains among precious stones and gold among metals." Teak wood has been since the standard species against which the quality and potential utilization of other tropical hardwood are being compared (Bhat and Hwan, 2007 and Kumar, and Kumar, and Fisher, 1998).

<u>Figure 2</u>. Cross-section of a plantation-grown teak log with its darker heartwood (Zanin, 2005).

3. Worldwide Teak Growth Requirements

Teak is indigenous in India, Laos, Myanmar and Thailand, but it is also grown in plantations on other tropical areas as seen of the map (**Fig. 3**). From the very restricted number of the countries where teak occurs naturally and the current plantations established worldwide, it seems obvious that teak is well suited within the boundaries of the tropics: 23.5^{o} Latitude North and 23.5^{o} Latitude South. Sudan is well positioned on the Northern part of the Tropics, opposite to South India and Thailand, countries hosting the natural habitat of teak in contrast to Indonesia the world market leading producer. With such a privileged position, South Sudan should theoretically be among those countries dominating the world market in teak production.

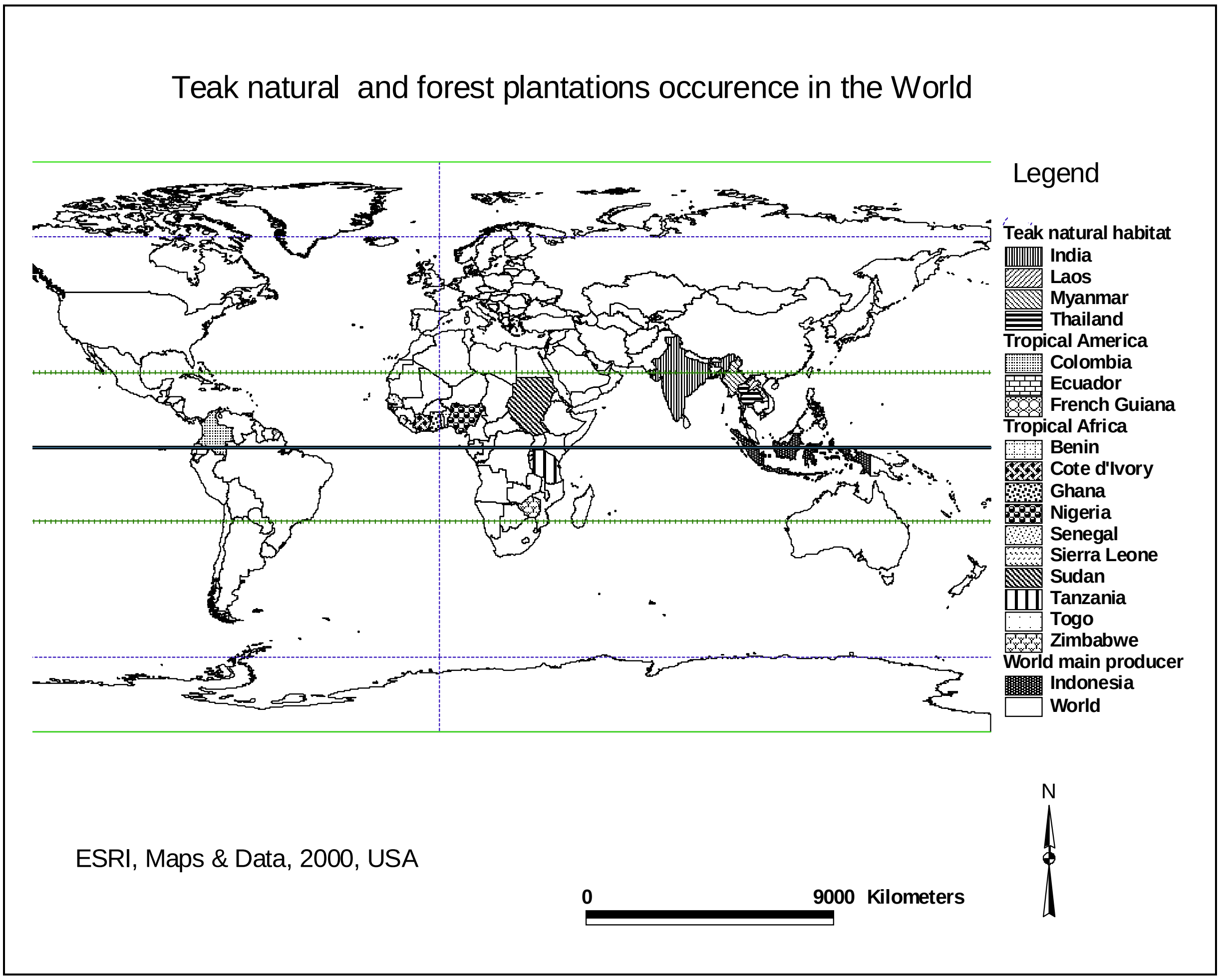
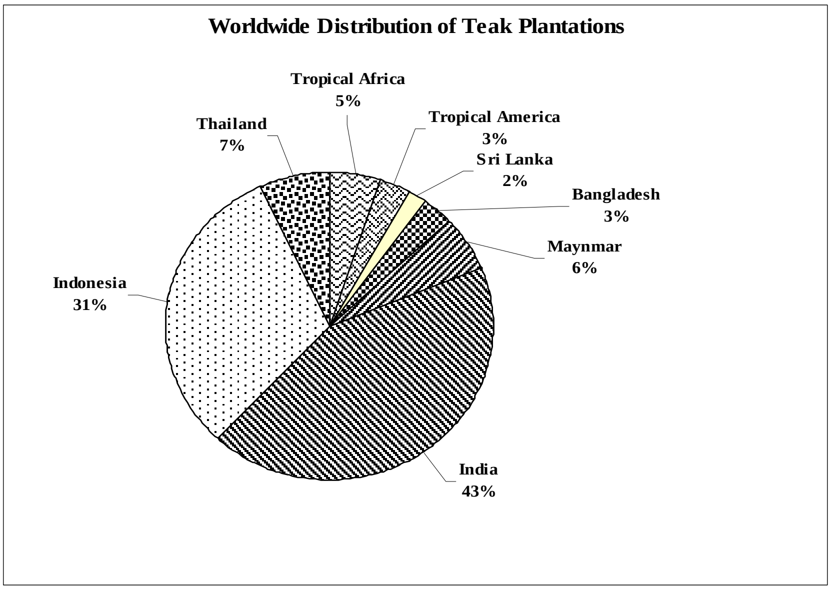


***Figure 3*. Teak-growing countries**

Despite the fact that teak plantations have been established in many tropical countries many years ago, the general view is that available data from these plantations are quite scarce. The reasons for this are multiple and many are attributed to the fact that no records are being kept because the key persons undertaking these researches often leave with whatever they found or simply because the key personnel does not trust the previous ones, thus restarting the work all over again (Evans and Turnbull, 2004).

However, the fact can also be attributed to frequent political conflicts in tropical countries where buildings are destroyed and any possible data records destroyed with it, which is the present situation in South Sudan (USAID, 2005). As Raymond (1996) stated, normal growth rates in teak are generally lower than in pines, eucalyptus or other plantation species.

It must be remembered that teak is planted for high valued timber and not for rapid volume production; a very rapid growth rate is likely to be detrimental to the quality of the wood produced. The implication is that due to the relatively long rotations involved with teak and other hardwoods, it is difficult to find investors who are prepared to lock up financial resources over the long time required. Such difficulties particularly face local investors in tropical countries (Raymond, 1996).



<u>Figure 4.</u> Worldwide distribution of teak plantations as percentage of the world total planted area (Bhat and Hwan, 2007).

Beside India, one of the three countries hosting the natural habitat of teak, world plantations and hence the market for teak is dominated by Indonesia (**Fig. 4**). In the worldwide distribution, the place of South Sudan as teak producer can be seen as a drop of water in the sea compared to the whole distribution of teak worldwide.

3.1. Climate

Country		MAR (mm)	MAT (°C)	ASL(m)
Natural habitat[*]		**1250-3750**	**Min 13-17 Max 39-43**	na[†]
Indonesia (Eastern Java)[‡]		1511-2108 (7months wet season; 5monts dry season)	30-32	100-1000
India[§]	**Central**	1600-1800 (monsoonic season)	25	na
	South (Nilambur)	>2500 (monsoonic season)	Min 19 Max 35	100-150
	South (chhindwara)	235-1247 (monsoonal)	Min 20 Max 29	410-457
Eastern Panamá[**]		2300	23-27	na
NW Costa Rica[††]		2900	26-29	90
Benin[‡‡]		1100-1150	25-29	40-80
Liberi[§§]a		2223-3221	25-27	na
Togo[***]		1200-1500	na	na
SW Cote D'Ivoire[†††]		1700-2100	na	110-200
South Sudan[‡‡‡] **Yambio-Nzara**		**1350-1600 (over 6-8 months)**	**28-35**	**800-1000**

.

<u>Table 1</u>. Climatic data of different tropical countries areas under which teak occurs naturally and/or as forest plantations (MAR: Mean Annual Rainfall, MAT: Mean Annual Temperature, ASL: Above Sea Level, Min: Minimum, Max: Maximum).

[*] Pandey and Brown (2002)
[†] na = no data available
[‡] Moh. Na'iem (2005)
[§] Sonali Saha (2001) - Bhat and Hwan (2007) -Chandrashekara (1996) - Pande (2004).
[**]Zanin (2005)
[††]Alvarado (2006) - Pérez (2005) -. Pérez and Kannien (2005).
[‡‡] Drechsel, Schmal, and Zech (1991)
[§§] Drechsel, Schmal, and Zech (1991)
[***]Dzila, Kokutse, Bailleres, Stokes, Kokou (2004)
[†††]Pourter; Jans; Bongers; Rompaey (1994)
[‡‡‡]Ayoub (1997) - Kamal and Badi (1989) - Comboni (2003) - Rozanov (2007).

Within these boundaries, teak occurs naturally in moist and dry deciduous forests below 1000m elevation in localities with annual rainfall of 1250 to 3750 mm, minimum temperature of 13^o to 17^{o}C and maximum temperature of 39^o to 43^{o}C (Pandey and Brown, 2002). Some climatic data from different countries managing teak plantations are grouped in **Table 1** above.

Table 1 shows that the mean annual rainfall generally varies between 1100 mm and 3750 mm with the lowest mean being recorded in Tropical Africa (Benin) and the highest in the countries hosting the natural habitat of teak (Myanmar and Thailand). The minimum and maximum mean annual temperatures range from 19 to 43^{O}C respectively. The hottest areas host the natural habitats of teak. These results can be explained by the fact that teak is recognized as a shade free tree species requiring a high level of sun radiations (Pérez and Kanninen, 2005). However, one of other main requirements is the occurrence and length of the dry season during which the species looses its leaves, a time during which the hard wood grains are expected to strengthen.

In the present case, 5 to 6 months of the dry season seem to be the optimum as is the case in Indonesia. Despite the slightly longer dry season of South Sudan, the data recorded for its Mean Annual Rainfall (MAR) and Mean Annual Temperature (MAT) are both higher than those of a number of other teak-growing countries of Tropical Africa such as Benin and Togo and are even higher than those of Central India - one of the three regions where teak has its natural habitat. The MAR of Nzara (1350-1600 mm) is within the boundaries of the natural habitat of teak (1250-3750 mm) and Central Indonesia, but most importantly, it is even higher than the records for the area of South India, meaning that the Nzara receives enough rainfall for the purpose of teak growth. The same is to be said for the MAT since teak is a shade free species requiring high sun radiation.

3.2. Soil

Due to the fact that climatic factors such as rainfall and temperature among others edaphic factors have impacts on plant physiological development and the life of micro-fauna which are responsible for tree litter decomposition resulting in the formation of soil organic matter, climate needs to be considered as the first edaphic factor during the process of establishing a site's suitability.

According to Mallapureddi (2002), the prime controlling factor for development of organic matter is climate, through its influence on litter production and its decomposition. However, the substratum on which plants are established also plays a crucial role not only because it anchors the plant of root system but moreover, it is the supplier of plant mineral nutrients. The worldwide suitability of growing teak in the tropics, can be seen in **Table 2**. Teak grows well on sandy loam soil implying good water drainage with a depth >90cm, and near neutral status: pH of between 6.5 and 7.5 (Zanin, 2005; Alvarado, 2006). The main soil physical characteristics for teak suitability are these of Sandy Loam texture on a parent material derived from plutonic (granite) and metamorphic (gneiss). The pHs values cover a wide range. But, when considering the recorded data of India and Myanmar, the pH interval 6-8 measured in H_2O can be regarded as the best optimum.

Country		Texture	Soil-Type	Parent rock	pH
Myanmar[*]		SandyLoam	na	na[†]	6.5-7.5
Indonesia (Eastern Java)[‡]		na	Karst, grumusol	na	na
India[§]	**Central (failed)**	Clay	Vertisol	Basalt, Sandstone	na
	South (chhindwara)	Sandy Loam	na	Alluvium	7.9
	South(Nilambur)	Sandy Loam		Laterite	na
NW Costa Rica[**]		Clay Loam	na	na	5.2
Benin[††]		Clay	Eutric, Calcic Vertisols	Clays, Marls	5.5-8
Liberia[‡‡]		na	Ferralsols, Cleysols	Granite, Gneiss-Diorite	3.8-5.2
Cote d'Ivoire[§§]		Clay Loamy	na	Granite, Gneiss	na

***Table 2.* Soil Characteristic Data of Different Countries under Teak Plantation Areas**

[*] Pandey, and Brown, (2002)
[†] na = no available data
[‡] Moh. Na'iem (2005)
[§]Saha (2001) - Bhat and Hwan (2007) - Chandrashekara (1996) – Pande (2004).
[**]Alvarado (2006) - Pérez (2005) – Pérez and Kanninen (2005)
[††] Drechsel, Schmal , and Zech (1991)
[‡‡] Drechsel Schmal , and Zech (1991)
[§§]Pourter, Jans; Bongers; Rompaey (1994)

3.3. Teak Productivity

According to Ball, Pandey and Hirai (1999), most of the teak yield tables refer to fully stocked stands. An important feature of all the yield tables of teak is the early culmination of Mean Annual volume Increment (MAI: m^3/ha/yr), generally between 6-20 years. However as these authors conclude, since teak has been planted and managed for log timber; log size therefore plays the decisive role for harvesting rather than the age of maximum volume production. The rotation age of plantation teak in its natural range varied between 50-90 years while outside its natural range it is between 40-60 years (**Table 3**). For the same reasons already enumerated earlier, few data relative to the management of tree plantations and teak in particularly are lacking in tropical countries. From countries with some available data, teak performance is generally low (**Table 4**).

One of the other main reasons beside those earlier mentioned is attributed to plantation management. As Raymond (1996) observed from teak plantations in Central America and the Caribbeans, very few teak plantations are well-managed in these areas; there is much room for improvement. According to that author, the aim should be to obtain at least 8m^3/ha/year, to ensure that goods and services are adequately provided and to distribute the benefits, notably profits, equitably amongst the actors. Despite the less well managed teak plantations in the tropics some countries including tropical Africa have high performance productivity on a world scale. **Figure 5** compares the teak best productivity performances with the available data of South Sudan teak plantations (**Table 4 and 5**).

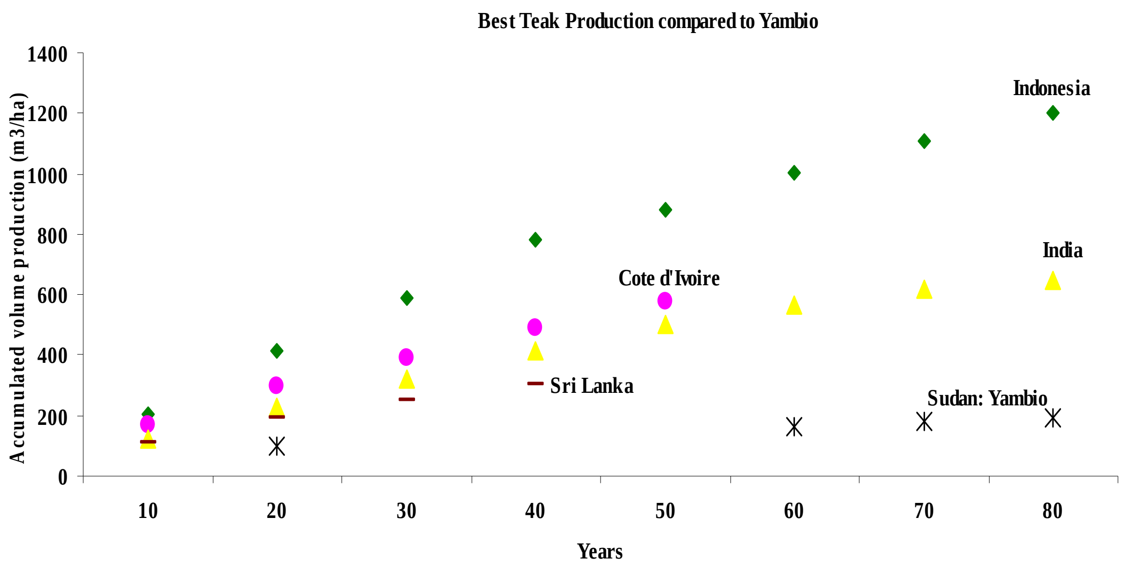


Figure 5. ***Teak productivity performance as accumulated volume (m^3) per year (Adapted and modified from Raymond, 1996).***

The accumulated volume of production (m^3/ha) for Indonesia surpasses most observations around the world. The maximum mean annual increment produced in this case is 21m^3/ha/years at 15 years of age and an annual increment is maintained at or above 15m^3/ha up to 80 years

(Raymond, 1996). On this scale, South Sudan, that is Yambio, registers the lowest and stagnant performance with an annual increment of approximately 2m^3/ha up to 80 years.

Year	**Accumulated Volume production (m^3/ha)**					
	Indonesia	**Cote d'Ivoire**	**India**	**Trinidad**	**Sri Lanka**	***Sudan (Yambio[*])***
10	207	170	123	130	110	
20	412	295	226	250	192	*97*
30	591	393	318	330	249	
40	784	489	416	380	301	
50	880	579	500	413		
60	1002		564	440		*166*
70	1106		616	460		*182*
80	1200		648	479		*192*

Table 3. ***Tropical teak best performance productivity (Modified from Raymond, 1996).***

The data in **Table 3** were used to compile **Figure 5.** Even though these data were published some 10 years ago. The place held by Indonesia as the main producer of teak on the world market is expected to remain for a long time since even the short rotation of the stand is of at least 40 years.

Site		**Age (Year)**	**Volume (m^3)**	**MAI[†] (m^3/ha/yr)**
Kagelu[‡]		13.5	25.2	1.87
		14.7	33	2.24
		20	44.4	1.48
Katire[§]		**11**	**62.2**	**5.65**
Nyin Akok[**]	**Good Site**	**18**	**77.8**	**4.32**
	Moderate site	18	32.8	1.82
Yambio		***18***	***87.1***	***4.83***

Table 4. ***Current performance of teak plantations in South Sudan; yield without proper thinning management (Kamal, Badi El Houri, Aziz and Bayoumi, 1989).***

According to Kamal et al (1989), no figures of teak final yields are available for South Sudan. The data of **Table 4** are from scattered sample plots. These records give a total volume overbark

[*]Kamal, Badi El Houri, Aziz and Bayoumi 1989
[†]MAI: Mean Annual Increment (m^3/ha/year)
[‡]In the Equatoria province but North of study area
[§]In the Equatoria province
[**]In the Bahrl El Ghazal province North of Equatoria province

down to 5.1 cm top diameter. In that Table, Yambio has the highest volume production (87.1m^3) and share the higher Mean Annual increment (MAI) (4.87m^3/ha/yr) with Katire.

Such a high performance is attributed by these authors to the geographic location of Yambio and Katire which are further south in the Equatoria province in comparison to Kagelu and Nyin Akok, located in the further Northern part of the same province.

Site	Age (year)	Volume (m^3)			MAI (m^3/ha/yr)
		Final Yield end rotation	**Yield from thinning**	**Total harvest**	
Katire and Yambio	60	81	85	166	***2.77***
	70	***90***	***92***	***182***	***2.6***
	80	98	94	192	***2.4***
Kagelu good site	60	61	58	119	1.98
	70	67	62	129	1.84
	80	73	64	137	1.71
Kagelu poor site	60	40	31	71	1.18
	70	44	3	77	1.1

***Table 5.* Sudan teak plantation yields expected under proper thinning management (Kamal, Badi El Houri, Aziz and Bayoum1989).**

These authors comment that if proper thinning is carried out, based on Indian data the yield presented in **Table 4,** could significantly be increased and lead to values of **Table 5**. At the end of a long rotation of 70 years, a total harvest of 182 m^3 (1,5 cm overbark) is expected at both Katire and Yambio. More than half (92 m^3) of that total volume would have been obtained as intermediate return due to thinning operations. Such a considerable partial return is necessary to compensate for all the efforts deployed in the management of plantations prior the long term final return. It also guaranties the quality of the final wood product in terms of particularly the diameter size of the logs at the end of the rotation length.

4. Study Area: Nzara Southern Sudan

4.1. Geographic Location

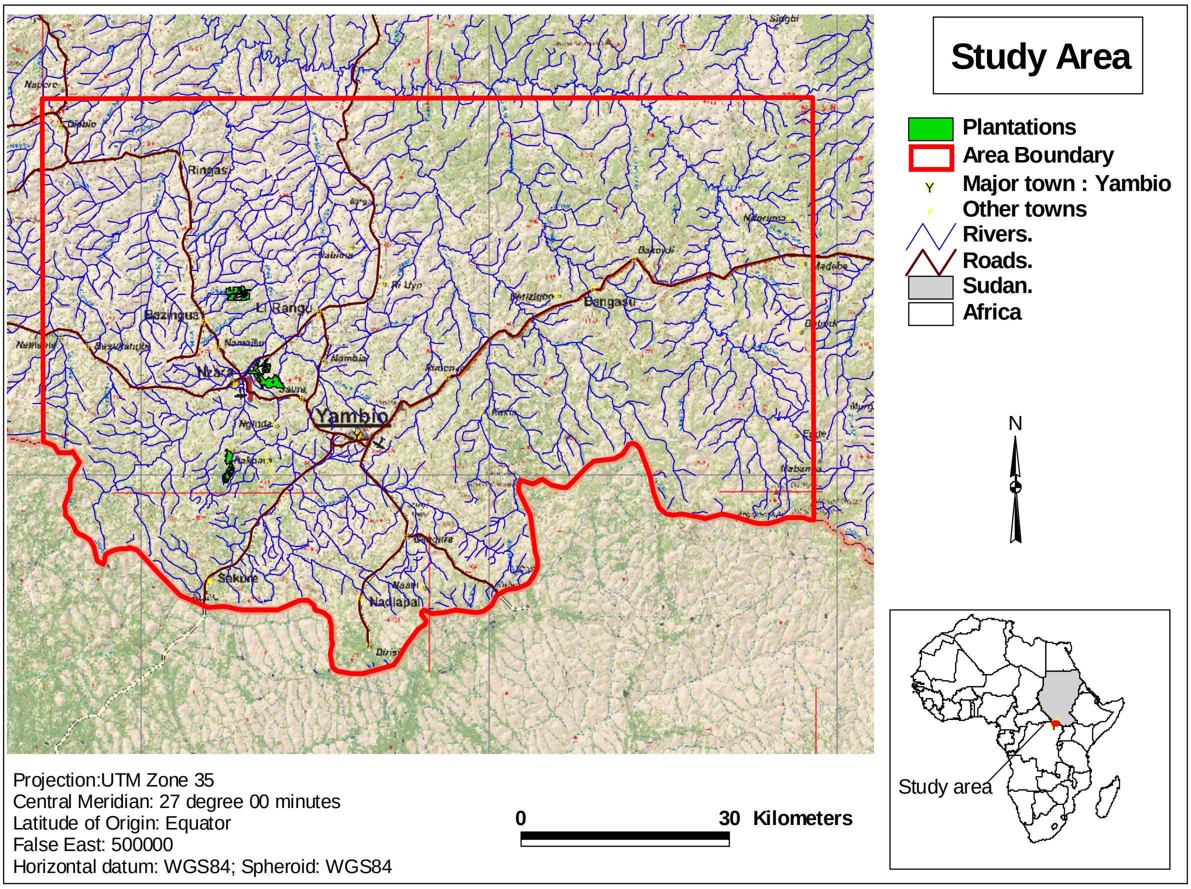


Figure 6. ***Geographic boundaries of the study area including current teak plantations***.

Nzara is some 25km North-West from Yambio. The captive feature of the study area is the many meander rivers deriving from the Nile. The presence of these meander rivers is crucial for providing water to the plantation stands. In any of these cases, the result might be that of less amount of water being efficiently stored as underground water for plants use during the long dry seasons.

4.2. Climate

The climatic information given below is adapted from the Comboni (2003) report, a hydrological company operating in the Nzara and from the Rozanov (2007) report. While the climatic data from the former are directly related to the area, those of Rozanov (2007) are mostly related to Yambio, a town about 20 km from Nzara. From these sources, it emerges that the Nzara area, like most of the Western Equatoria regions, is characterized by a hot, tropical, semi-humid lowland climate, with a single prolonged wet season and longer dry season.

4.3. Rainfall

The main source of rainfall over Southern Sudan is the South Atlantic Ocean. The elevated hills and plateaus that form the boundary of the great central plain receive mainly orographic rainfall: when air mass forced from low elevation to a higher elevation, precipitation occurs as warm and moisture laden air is forced upward into colder layers of air. However, convectional storms cause most of the rain over the vast plain, as the air near the ground heats up during the day, expands, rises and cools down. As a result, most of these violent but highly localized storms occur in the late afternoon and evening. Frontal rain is the third form of precipitation: it falls at the boundary of warm, southern air masses, which override colder and denser northern air.

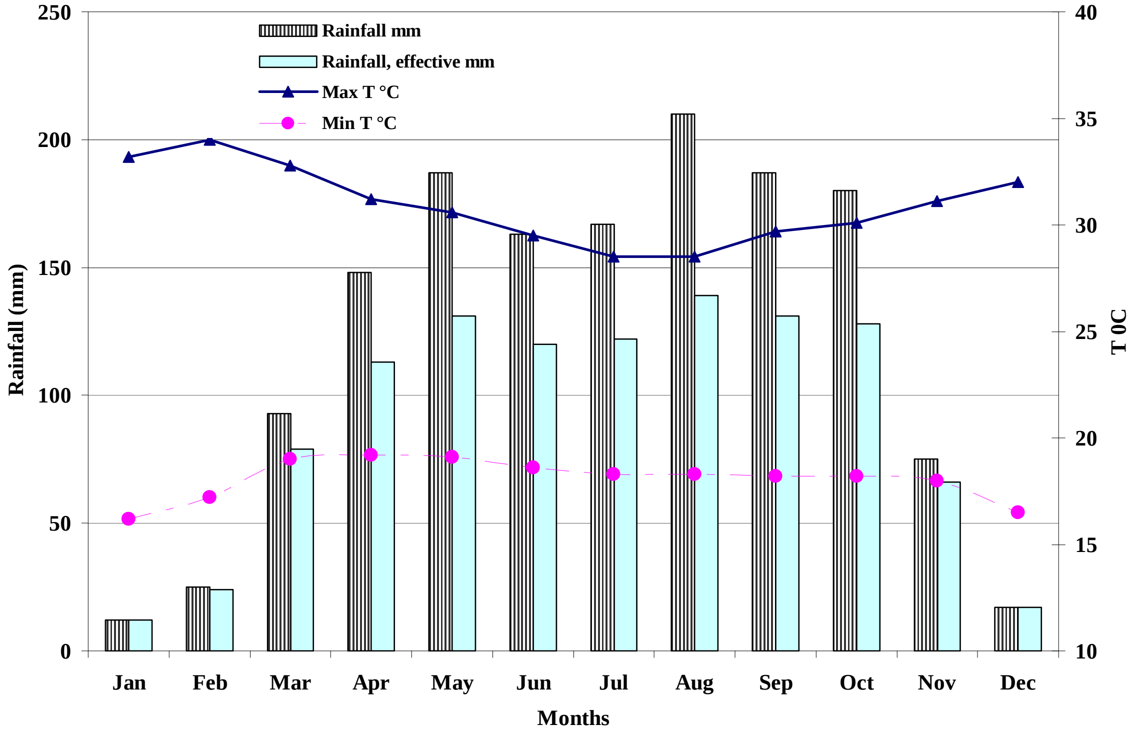


***Figure7**. Long-term monthly climatic data for Yambio weather station: 650 m above sea level (asl), latitude N4°34´, longitude E28°24´ (Data from Rozanov 2007).*

The regional average annual rainfall is between 900mm and 1600mm: 900-1300mm in the ironstone region towards the North and 1350-1600mm in the region closer to the Congo border; a region qualified as the Green Belt (Comboni, 2003). The dry season occurs between November and March and lasts three to four months.

From **Figure 7** a typical equatorial climate can be seen, with a nearly constant temperature over the year and a slightly hotter dry season from November to February. With a mean annual temperature of 18-31^{o}C for the minimum and maximum respectively and total yearly rainfall of 1464 mm, the climate is well within the appropriate range for teak growth as compared to ranges already shown in **Table 1.**

4.4. Temperature

The average temperature at many places in the Western Equatoria region is estimated to be approximately 28^{0}C, with mean diurnal amplitude of 14^{0}C. The average monthly maximum and minimum temperatures are close to 35^{0}C and 21^{0}C respectively. The period from January to April is relatively hot (Comboni, 2003).

4.5. Evapotranspiration: Surface Evaporation and Plants Transpiration.

The actual evapotranspiration (Et) is a function of the amount of rainfall and the other outgoing water balance components, surface runoff and groundwater recharge. The lack of relief, combined with the poor infiltrability of the topsoil, minimize the amount of lateral and vertical drainage. As a result, widespread flooding occurs in the lower parts of the plain. Eventually, almost all the surface water retained in ponds and swamps will evaporate during the dry season. It thus follows that the actual evapotranspiration is extremely high: possibly as much as 90-95% of the annual rainfall (or 870-915 mm/year), (Comboni, 2003).

4.6. Physiography

In the Comboni (2003) report, it merges that the morphology of the study area is characterized by relatively flat topography marked generally by subdued plains and occasionally interrupted by relatively developed hilly Basement structures. Wide but shallow riverbeds, in most cases with stagnant or poorly flowing streams and rivers characterize depressions between these relatively hilly Basement structures. Generally most of these depressions exhibit impeded drainage, and are seasonally swampy. Soils developed within this environment are characterized by a high portion of clays and silts, which reduce infiltration and maintain the growth of swamp vegetation**.**

4.7. Geology

Comboni (2003) pointed out that detailed geological data or maps of the Nzara area do not exist. However, these authors agree that a number of records obtained from the UNICEF-OLS (Yambio) contain useful general information on the regional geology which gives the description as follows:

The dominant geological feature of the Southern Sudan is the "cuvette", a great depression formed through the sinking down of the land surface, carved by erosion out of the crystalline complex of rocks. The floor was once covered by continental deposits of the Nubian Series, most of which was later removed by erosion prior to the development of the depression. The rocks of the study area are however almost completely masked by compact ironstones and lateritic soils. It is probable that the ironstones of this area were formed during two periods: a) an *older* ironstone (mid-Tertiary age) formed before the depression, during a lateritic climate stage. The depression is now filled with deposits of the Umma Ruwaba series; b) the *later* lateritic climate (late-Tertiary or Quaternary) produced red laterites common in the study area (Comboni, 2003).

The area is generally covered by undifferentiated basement complex rocks mainly of Precambrian age, with sediments overlying them especially within the valleys. The basement rocks are comprised of granitoid gneisses, muscovite-biotite gneisses, quartzites and quartzitic pegmatites, foliated granites and granodiorites, schists and paraschists, feldspathoidal soda syenites, phyllites, slates, shales and sediments of various ages ranging from mesozoic to recent time. A mixture of mudstones, sandstones, sands, ironstones, silts and clays, are thus deposited not formably over undifferentiated rocks of the Precambrian Basement System, and their sequences vary from area to area (**Fig. 8**).

Both Rozanov (2007) and Comboni (2003) observed that in the field various recent alluvial and colluvial sediments largely conceal the nature of the bedrock. And that further North-East from the Congo border these sediments become a continuous laterite (iron plateau), which extends in direction for 20-100 km. Subsequently, the South-Western boundary of laterite shown on the geological map only indicates the continuous laterite of substantial thickness. In fact, the laterite still extends to the South-West of the line dentritic pattern capping the watersheds.

From Rozanov (2007) previous authors such as Lebon (1959; Rozanov, 2007), separated this Ironstone Plateau of South Sudan into Western and Southern parts recognizing the outcrop of basement rock which separates both. The study area is thus in the Southern part of the Ironstone Plateau or, according to another delineation attributed to Morison et al (Rozanov, 2007) within the Watershed Region, often referred to as Yambio forest region. The region is dissected by a dense dentritic network of permanent and intermittent channels. The large valleys display pronounced terraces. The ironstones are generally cemented materials of coarse sands, quartz, gravel and iron oxide. The hardening of laterites is attributed to normal desiccation of free drainage water during the dry season. The laterite matrix is normally impermeable though drainage is generally fair through cracks and other discontinuities.

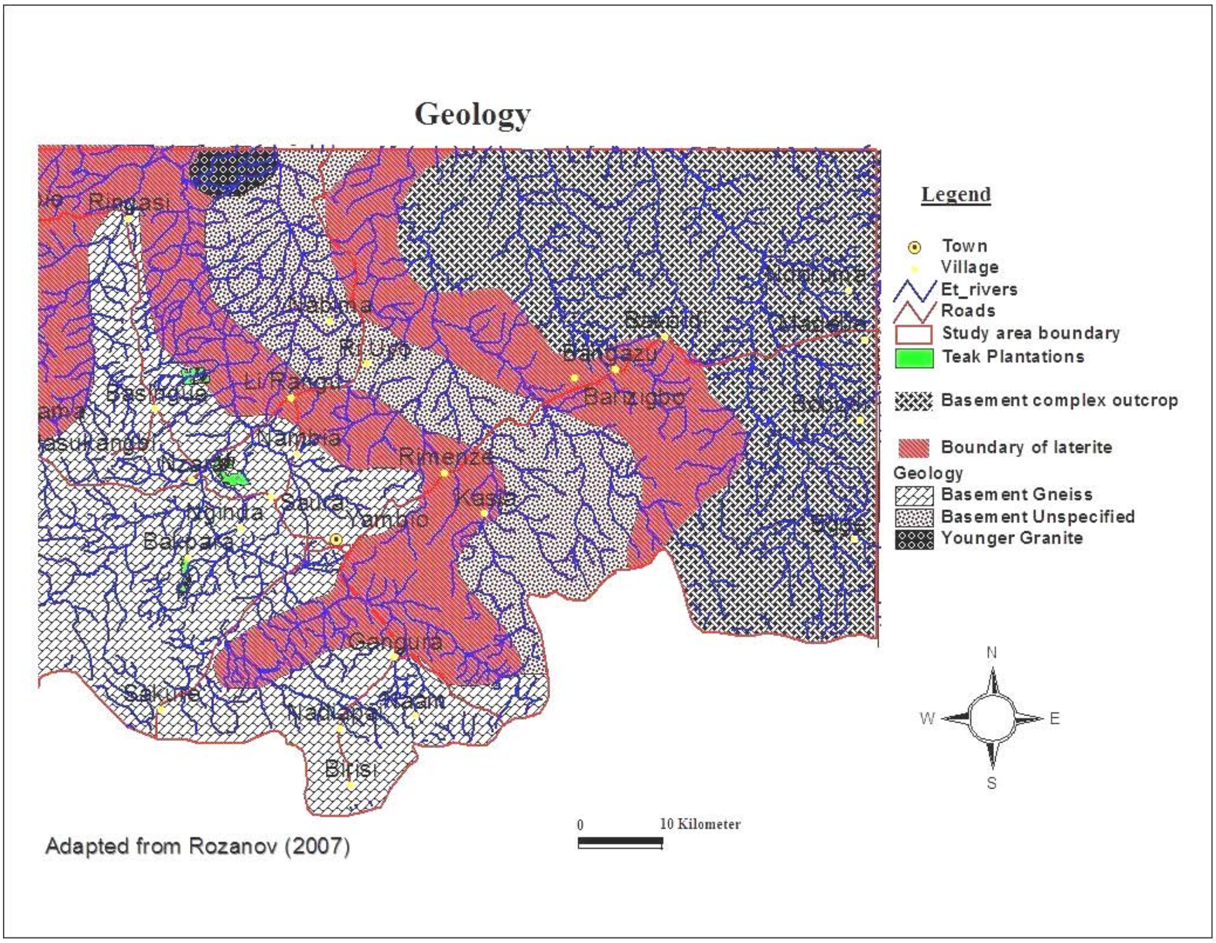


Figure 8. ***Geological boundaries of the study area including the position of current teak plantations (Adapted from Rozanov, 2007).***

The ironstones are thus common on low ground but are rarely found in river valleys, except as ironstone gravel. In slightly higher areas, the ironstones (concretionary or honeycomb structured) form sheets that cap the small hills. Where the lateritic sheet is thick, the lower part is normally of non-ferruginous white kaolin deposit. In Nzara area, isolated small flat toped hills of various Basement rocks are capped with horizontal cakes of ironstone. The hills normally protrude above the plain at low relief often covered by a lateritic ferruginous deposit of generally soft, unconsolidated red clay (Comboni, 2003).

While the two bottom Southern plantations (Yoboa and Mabarizinga) have the Basement Gneiss as bedrock, the remainder plantation (Nagondi) is half way between the Basement Gneiss and the Laterite. From these special localizations, the deeper soils are expected to be encountered around the two previous plantations.

4.8. Natural Vegetation

Water is one of the principal factors determining the occurrence of vegetation. Since South Sudan is the part of the country receiving the highest (1350-1600 mm/month) rainfall over the year, it represents the greenest region of the country. The resulting natural vegetation is a mosaic of tropical rain forests and savannah. Towards the North on the Ironstone Plateau where the average rainfall precipitation is 900-1300 mm, the vegetation is mainly broad-leafed deciduous woodland. In the Green Belt: extending to the extreme southwestern portion of the Province towards the Congo border, vegetation is more luxuriant with occurrence of broad-leafed and bowl forest along perennial streams and in depressions (Comboni, 2003).

Rozanov (2007) also agrees that the tropical rain forests of South Sudan are not exactly a myth, but rather a subdominant fact. However, the latter author slightly diverges from Comboni (2003) report in that an eye-catching vegetation type in the area is rather dominated by moist savannah. His comment is that it seems that forest favors the recent sandier river terraces and spreads towards the watersheds. The closed-canopy forest borders the extensive wetlands in the well-developed floodplains. Soil wetness, and reduction conditions are the main edaphic feature of these plains, which support dense tall grasses, but very few trees can cope with this environment resulting in a sharp boundary between grasslands and forest. Wetlands and riparian vegetation are common throughout the study area and present open grasslands with rare acacia trees on the levees.

The Sudan Country Study on Biodiversity (USAID, 2004) also points out that approximately 68% of the country's forest biomass resources are found in the South and in the past, they accounted for approximately 85% of the total sawn timber produced. A number of the species found in the better watered portions of the South attain impressive sizes and produce high quality hardwood timber (e.g., *African Mahogany – Khaya senegalensis* and *Iroko*, sometimes called African Teak or *Mvule – Chlorophora excelsa*). Another – *Isoberlina doka*, was commonly cut for railroad ties because of its strength and durability. In fact, as concluded the (USAID, 2004), there are so many valuable and workable timber species in these forests of the South that it is surprising that a more sophisticated timber industry did not develop there. The presence of the rainforest in the South Sudan was notably documented by the FAO (Food and Agricultural Organization of the United Nations) as can be seen in **Figure 9**.

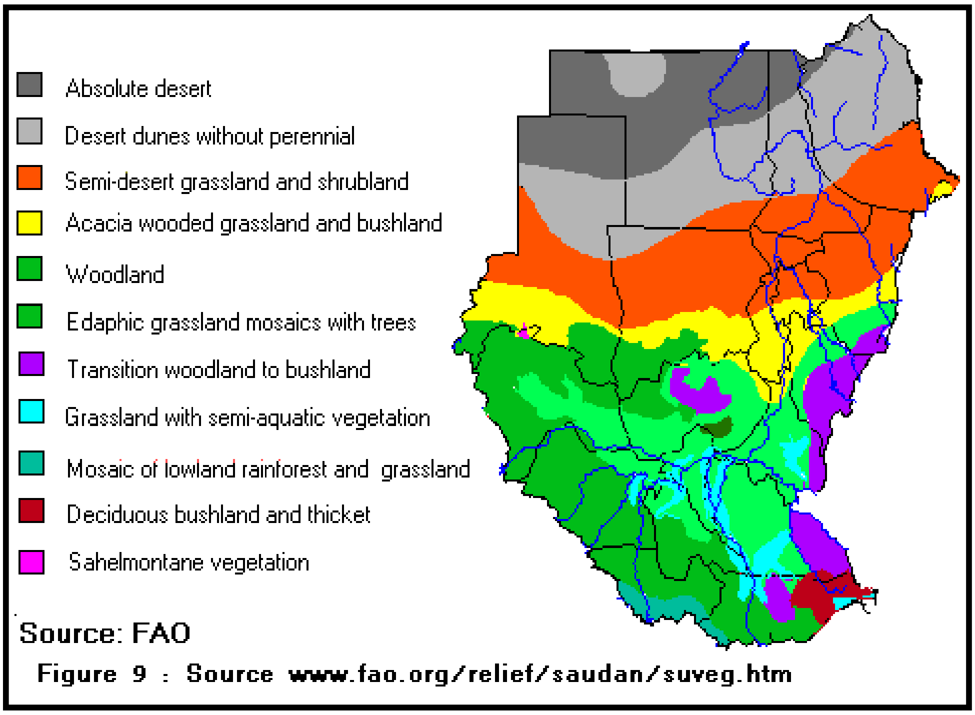


Figure 9. ***Sudan vegetation cover (adapted from FAO: www.fao.org/relief/soudan/suver.htm, retrieved 25 September 2007).***

Although its compilation date were not attached with the map of **Figure 9**, it still depicts a mosaic of lowland rainforest and grassland as the dominant vegetation of the Equatoria province around the study area located in the transitional zone between moist savannah and closed canopy forest. Only a small portion of the latter is found in South Sudan, while most of tropical Northern Congo Basin forest area lies to the South of the Congo-Nile watershed. The main three biomes occurring in the study area are the closed canopy, moist savannahs and alluvial grasslands comprising a dendritic mosaic **(**Rozanov, 2007**).**

The aerial photo in **Figure 10** shows the meandering rivers running through the area. The distribution of soil profiles show that the apedal deeper soils appear from the second terrace up to closer to the watershed and the shallow ones on the flood plain and first terrace. The observable natural boundaries of the natural vegetation here may be explained by soil depth sustaining trees from the second terrace to the watershed and the grass and/or shrubs on the flood plain and first terrace.

Figure 10. ***Aerial photograph of Nzara catena with opened profile pits position (Rozanov, 2007). This figure shows a typical river meander with insertion of the topography level of the study area: the flood plains, terraces and watershed. Main soil profiles occurring on these topographic levels are also presented. As can be seen, high canopy vegetation occurs on the second terrace and spreads onto the watershed related to the depth of the soil present at these elevations.***

4.9. Exotic Vegetation: Forest Plantations

The forestation potential of the Southern Sudan has been recognized since the colonial times and certain efforts of protection management were made to take advantage of the better growing conditions there. Three different kinds of forest reserves were gazetted: protection forests (typically, the "bowl" forests, along riverbanks and in the vicinity of the Roseires Dam); protection forests with utilization of net yield (typically on steep lands or in the hills); and sustained yield forests on which regeneration can be assured (many of which have been planted with teak and other species). Unfortunately, good data on the area of these many reserve forests and on the activities undertaken on them is presently lacking as records were lost or destroyed during the civil war (USAID, 2004).

However, most of the native trees of Sudan, as said Kamal et al (1989), do not possess the qualities of growth or the qualities of timber which are needed to realize the objectives of plantations. They are slowed down in growth, do not have clean stem form and their timber is not valuable. Introduction of exotics were therefore imperative. These were made by the Forestry Department for plantation purposes; some species were introduced by missionaries, administrator and other authorities. Among the earliest exotics introduced in Sudan is teak (*Tectona grandis*), introduced in 1907 or 1909 at Malakal on the grounds of the house of the Inspector of Egypt (Kamal et al, 1989).

The first plantation was established at Kagelu (Northern part of Equatoria province) in 1920. Subsequently, no more plantations were grown until 1932, when more plantations were made in Kagelu and a beginning at Nyin Akok near Wau (Norther part of Equatoria province).

Since then plantations have been established in many parts of the Equatoria and Bahr el Gazal Provinces and in a few areas elsewhere. The teak plantations of Nangondi, Yoboa and Mabarizanga on which this study focuses on, are among these few other areas.
According to Kamal et al (1989), it is uncertain from where the teak grown in Sudan was originally introduced, but by good fortune, straight-growing strain of good form was selected and this seems very suitable to the conditions under which it is grown. Seeds for local plantations are all collected from local trees of the same origin. Except from the informal cutting down of planted teak trees by thieves, no proper sylviculture operations have taken place since these plantations were established some 50 to 60 years ago. Such a situation of none thinning operations undertaken explains the dense tree stands (**Fig. 11**).

a. Teak trees in one of South Sudan plantations

b. Fallow land outside South Sudan Teak forest plantations

Figure11. ***Comparison of soil covers under teak plantations and fallow lands (see discussion on page 41).***

The soils under fallow lands are well protected from principally water erosion as they present considerable and diverse vegetative covers. In contrast, the soils underneath the teak plantations are barren. The teak roots exposed to the air express such a severe intensity of physical erosion due to water. In term of nutritive value, accumulation of organic matter under fallow can reasonably be expected in contrast to soils under plantations. The density of stand seen in the picture expresses a lack of sufficient sylviculture management, particularly thinning operations. The lack of such thinning operation explains to a large degree the thinner size of the stand stems.

II. MATERIAL AND METHODS

1. Soil Sampling

Soils of Nzara area were inspected and sampled at random by A. Rozanov in the vicinity of the three plantations – Nagondi, Yuboa and Mabarizanga. The reference of the sites as Nagondi, Yoboa and Mabarizanga will be referred to not only as plantations but as areas around these plantations. Twelve (12) pits were dug and described. In addition, holes were augered to a depth of up to 80 cm to confirm the sequence of horizons and depth to laterite at various locations. Forty (40) soil observation points were studied. Additional samples of sandy sediment in the drainage lines were collected. Sixty (60) samples as soil profile horizons were analyzed in total (Appendix B and C). The samples were oven dried overnight, ground and sieved through a 2 mm sieve. They were then packed in boxes for laboratory analysis at the Soil Science Department of Stellenbosch University.

2. [*]Soil pH: Hydrogen and Aluminum Saturation

The pH of soil samples was determined in both water (1:2.5 soil:water) and potassium-chlorite (1:2.5 soil:KCl) according to Pauwels et al (1992). Samples where the pH value in water were less than 5.5 were treated with 1M KCl (1:2.5 soil:KCl) and titrated with 0.01M NaOH using the Phenolphthalein (0.5%) as an indicator as recommended by Thomas (1982) and also Pauwels et al (1992). Hydrogen (H^+) and Aluminum (Al^{3+}) saturation were thus determined. The choice of 5.5 in water as a cut off value for pH determination of exchangeable Aluminum rather than 5.2 in KCl, was decided on account of the fact that the natural conditions of the weathering mechanisms involve water as a hydrolysis agent rather than KCl even though the primary intention of KCl uses is to test the presence of exchangeable Aluminum (USDA, 2004).

3. [†]Carbon: Nitrogen

The organic carbon and nitrogen as percentages were obtained by milling the 2 mm sieved soil and passing them through the soil Carbon and Nitrogen Euro Vector Elemental Analyzer.

Soil colour was described in the dry state by using the Munsell Soil Color Charts (1990).

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[*] See to Pauwels et al, 1992 and Thomas, 1982.

[†] Euro Vector Elemental Analyzer with Software Callidus Version 2E3 Serial Number 03392

4. [*]Texture

Texture was determined using both the Hydrometer and Chain Pipette methods as recommended by The Non-Affiliated Soil Analysis Work Committee (1990). In both cases, the samples were first treated with the Hydrogen-Peroxide 30% to destroy the organic matter compounds, Calgon (sodium hexametaphosphate: 4% and soda 1%) and Sodium dithionate (powder) to destroy Iron and Aluminum complexes.

The soil particles larger than 53 µm were further separated through a set of sieves of 0.5 (coarse)-0.25 (medium)-0.1 (fine) and 0.05 (very fine) mm respectively for sand grade determination. The South African Soil Classification System (Soil Classification Working Group, 1991) was used to grade the sand class. In the chart that was used, the percentages of fine and very fine sand were combined as fine sand.[†]

5. [‡]Free Iron and Aluminum

Filtrates collected from the texture extract samples already treated with Sodium Dithionite were used for Aluminum and Iron determination on the Atomic Absorption Spectrum (AAS) as recommended by Thomas (1982) and Pauwels et al (1992).

6. [§]Available and Total Cations and Phosphorous

For the sum of cations S-value (Mg, K, Ca and Na), the samples were first treated with Ammonium Acetate (1M NH_4OAc) at pH 7 according to Pauwels et al (1992) then passed through the AAS.

The available phosphorous was determined using the colorimetric Bray2 method (1, 2,4-Amino-naphol sulphonic acid and Boric Acid-Molibdate) following the method advised by Pauwels et al (1992). The total phosphorous using the colorimetric method of the warm digestive Nitric Acid (1:10 soil: nitric acid), washed with sulfuric acid and then treated with sulfomolybdic and ascorbic acid also following the method advised by Pauwels et al (1992).

Total potassium was extracted by boiling 5g of soil into 50mL of 1M (86mL pure HNO_3 in 1L water) Nitric acid during 10min and determined through the AAS as described by Falk and Krogstad (2005).

[*] The Non-Affiliated Soil Analysis Work Committee (1990)
[†] The gravel content was determined by considering the weight of all the soil particles larger than 2 mm mesh sieve.
[‡] Thomas, 1982 and Pauwels et al, 1992
[§] Pauwels et al, 1992

7. Statistical Analysis and Software

The three sites and two land uses were considered as the independent variables, the soil profile horizons as experimental units and all the physical and chemical properties at sites and land uses as dependent variables. General regressions were undertaken between sites (Yoboa, Mabarizinga and Nagondi) and land uses (Outside and Inside Plantation) soil horizons in respect of their physical and chemical properties. The Excel and Statistca7 Software programmers' were used**.**

The requirement of assumption for Normality and Homogeneity of Variances of each physical and chemical population properties means were first investigated. As none of the data set was normal, Non-Parametric F-test comparisons were carried out by performing the Kruskal Wallis Test on One Way-Analysis of Variances (ANOVA) by Ranks using STATISTICA 7 Software. The BOOTSTRAP Software (Efron and Tibshirani, 1993) was also used for further investigation on the assumption of normality and obtained the population means between sites. The BOOTSTRAP procedure consists in re-sampling a handful sample data from the original data set with replacement and this is done a 10.000 times. Through this approach, an estimation of the sampling distribution is obtained and thus an accurate estimation of an estimator of the original sample is deduced. The means and confidence interval graphs from the BOOTSTRAP test are presented and compared at the Kruskal Wallis Pvalue of 0.05 coded "P_{KW}". The BOOTSTRAP test was not performed on the land uses. Thus the population means confidence interval graphs are directly derived from the Kruskal Wallis One-Way ANOVA.

The P-value at the 0.05 level of Test for Homogenous of Variances coded "P_{HV}" were derived from the One Way ANOVA using the Hartley F-max, the Bartlett Chi-Square and the Cochran C tests.

III. RESULTS AND DISCUSSION

The establishment of forest plantations is often a subject of considerable hot debates between foresters and governmental agencies on one side and environmental organizations and local communities on the other. Forest plantations are usually assumed to limit or decrease the biodiversity of the natural ecosystem due to their uniformity on a wide scale but moreover, they are assumed to degrade in immediate terms the physical properties of the soils, and in long term due to the length and numbers of the stand rotation on site, they are also assumed to considerably affect the chemical characteristics of soils which as a whole ultimately become poor for food farming and/or cash crops. For these reasons, forest plantations are mostly established on marginal soils identified and classified as marginally suitable for food crops.

Foresters such as Raymond (1996) attribute these speculations on the effect of soil degradation attributed to forest plantations as the results of improper management of the stands rather than the nature of cropping system. Raymond (1996) for instance mentioned that there is not enough information to verify the deterioration of a site under several teak rotations. In contrast as that author argued second rotation of teak crops at Nilumar had suggested the opposite: an improvement of particularly the physical soil conditions. When certain deficiencies do arise after several rotations, it may be possible to rectify them by providing one or more rotations of an alternative species in a somewhat similar fashion to rotations of agricultural crops. Planting on good soils as Raymond (1996) continues does not necessarily affect food supplies; but teak is a legitimate competitor to non-food producing crops like cotton that can be much less environmentally friendly than teak, as e.g. large amount of insecticides are often used during cultivation. That author concluded that assessments which take into account social and environmental costs and benefits should be carried out before the land use decision is made.

In the discussion of the soil characteristics which will follow, the first criterion of classification will be that of site locations, that is: Yoboa (785ha); Mabarizinga (531ha) and Nagondi (613ha) as independent variables. After the investigation of any soil characteristic differences under the effect of these sites is carried out, a further investigation under classification of land uses will also be taken. Such a further grouping investigates the effect of land use on soil characteristics which could have been masked by the first grouping of sites.

In discussing the Burma politics of land use, i.e. from crop shifting cultivation to teak-forest, Raymond (1994) observed that crop cultivation was viewed by many colonial officials as a destructive and primitive form of agriculture whereas teak forest cultivation was of more 'useful' ends. This view of the latter guaranteed its popularity in a broader imperial context and even today, the use of commercial tree plantings remains an acknowledged agroforestry technique and is promoted as a cure for various social and ecological problems.

1. Soil Physical Characteristics: Texture and Structure

1.1. Soil Texture and Structure as Site dependent: Yoboa, Mabarizinga and Nagondi

The complete results of soil physical and chemical characteristics are presented in Appendixes B and C respectively.

As Fearnside and Niwton (1999) pointed out, one of the most important characteristics of the soil fertility status is its texture; the balance between mainly sand and clay. Very sandy soils are poor for plant growth due to their lack of cations holding sites which are consequently leached away. Sandy soils do not hold water well and expose plants to drought stress during the dry periods.

Clay soils on the other hand have more sites for holding cations and water. However, the type of clays involved can be detrimental since very heavy clay of the smectite type with very firm structure can have small micropores from which removing water during the dry period will require an undue exertion of force by the plant roots. Heavy clays also can lead to soil compaction when the soil dries out resulting in high water runoff and therefore less soil water infiltration during the rain or irrigation. Moreover, clay minerals of the structure 1:1 soil as Kaolinite have low cations exchange sites; the result being a high leaching of cations down the profile or laterally washed out of the profile through erosion.

The type of clay mineral affects K availability, potassium only has one plant-available form: K^+, but there are certain soil clay types that hold or trap K and control its availability - mica minerals (Schroth and Sinclaire, 2003). However, the K contained in these minerals is fixed between the mineral layers, making it virtually unavailable to plant roots. Soils containing predominantly kaolinitic clay have less exchangeable K to release than soils that have higher percentage of illite and vermiculite clay. Binkley and Giardina (1998) for instance stated that the composition and productivity of forests differ strongly among sites that differ in soil properties. Dickinson, Greenfield and Ross (1989), also mentioned that humus and clay are very small particles - colloids; that they have important characteristics such as large surface area, which is electrically charged (negatively) and are able to attract positive charges (Ca^{2+}, Mg^{2+}, K^+…) and bind them on their surface. The colloids therefore provide storage for available forms of certain plant food elements.
According to Sanchez (1976); Pancel (1993); FAO Unesco (1974) Ferralsols or Oxisols (USDA, 1999) are the most widely spread soil types over humid and sub-humid tropics. They are characterized by a ferralic B horizon dominated by a SandyLoam texture: clay proportion in weight at least of 40% and of clay type Koalinite with sesquioxides dominated by goethite (FeOOH).

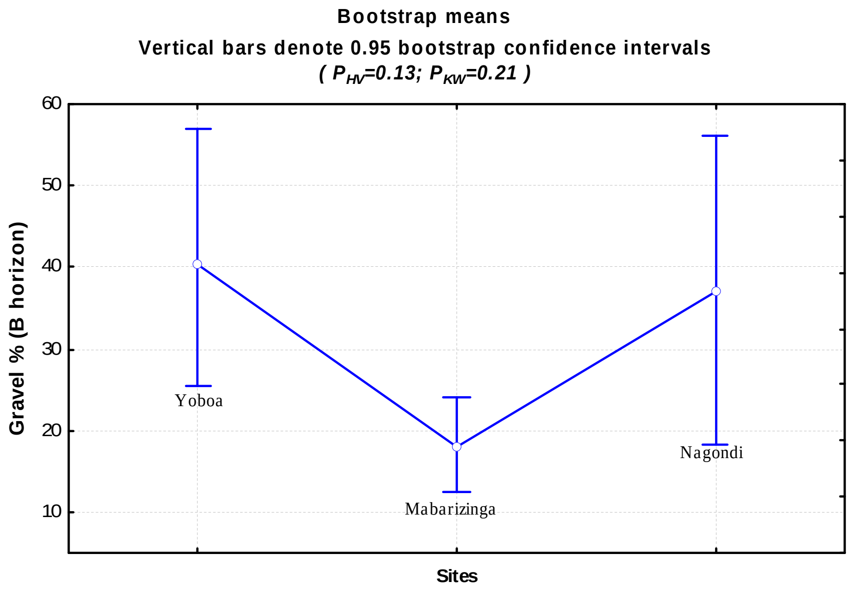
The analysis results obtained on texture and structure within the three sites did not show any statistical significant differences as seen from **Figure 12**. In other words, the mean levels of gravel, sand, silt and clay in a longer term will be similar without any account of the sampling site under which they will be sampled.

Despite the lack of differences between the population means, a number of concerns need to be raised. The first concern is that of experiment design itself, the sample sizes and the use of statistics as a tool of comparison. Statistical software as a tool of comparison is more reliable in cases where experimentation is carried out rather that in this case of purely geographic observation. Secondly the sample size often required for such software to make the comparison more reliable goes from at least 60 experimental units (Clewer and Scarisbrick, 2006) comparing to the 10 maximum experiment units we had. The third concern is related to the choice of the Statistical Test use. Indeed, although Non Parametric tests such the Kruskal Wallis are considered similar to the One Way ANOVA, their comparison is carried out on ranked medians rather than on means themselves (Clewer and Scarisbrick 2006). The probability cut off level of 0.05 might also have been too high to pick up the possible difference between the analyzed properties.

From **Figure 12** and **Figure 13** for instance one can agree that there is no significant difference of gravel, sand and clay percentage between the three sites on the A (0-20 cm) horizon. But when it comes to the B (20-50 cm) horizon a certain doubt arises due to the non-parallelism of the means on the graph. From these and without rejecting the non significant differences obtained among these population means properties, Mabarizinga site has the highest level of clay with a mean value of more than 45% and the lowest level of gravel at the B horizon. On the other hand, Nagondi registers the lowest level percentage content of clay (<32%), together with Yoboa they have the highest level of gravel percentage content i.e. >40 % for Yoboa and >37% for Nagondi at that same B horizon.

Insignificant difference was found between the sites and all horizons as all Kruskas Wallis p-values: 0.52, 0.21, 0.76 were larger than 0.05. The mean variations are however higher in Nagondi and Yoboa for gravel content.

Despite none significant differences between all the physical characteristics at all three sites and horizons at the considered p-value, the variation of the mean at the Mabarizinga site for gravel is the lowest in comparison to the two others sites. This suggests a lower degree of erosion which would have otherwise resulted in the accumulation of gravel at the Mabarinzinga site. This seems to be confirmed by that site wider mean variation of clay in contrast to Yoboa and Nagondi in that order of mean variation decreaseness. Nangondi on the other hand has the wider mean variation of sand which suggests that compared to Yoboa it should be expected to be subjected to more intensive physical erosion beside the a certain parent material difference.



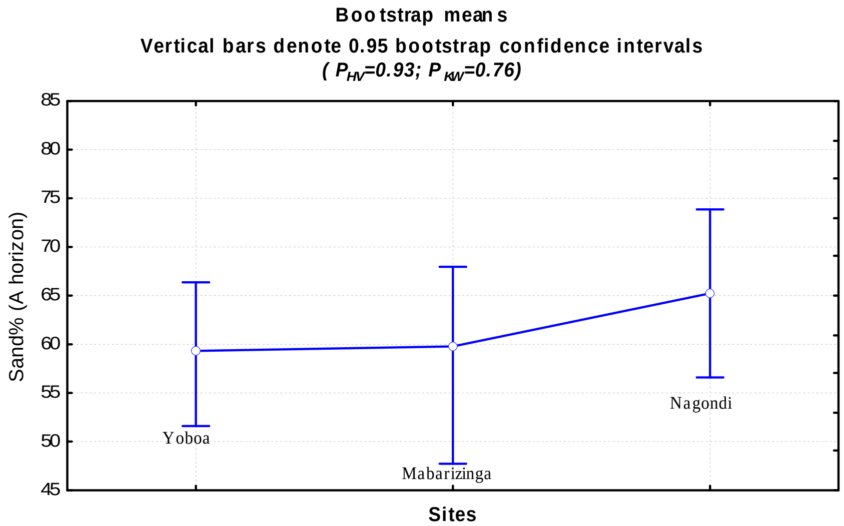


***Figure 12a.** Statistical Comparative results of soil gravel and sand and as a percentage between the tree sites at both A (0-20cm) and B (20-40cm) horizons.*

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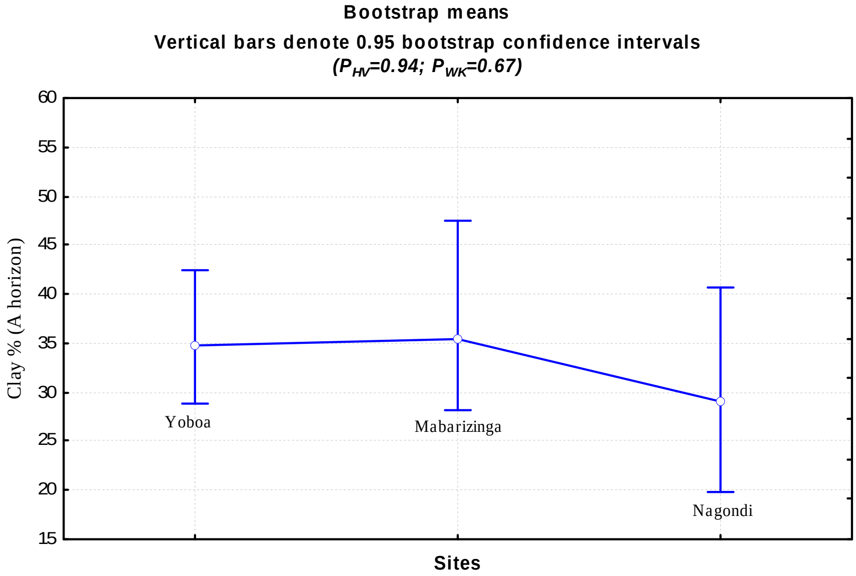
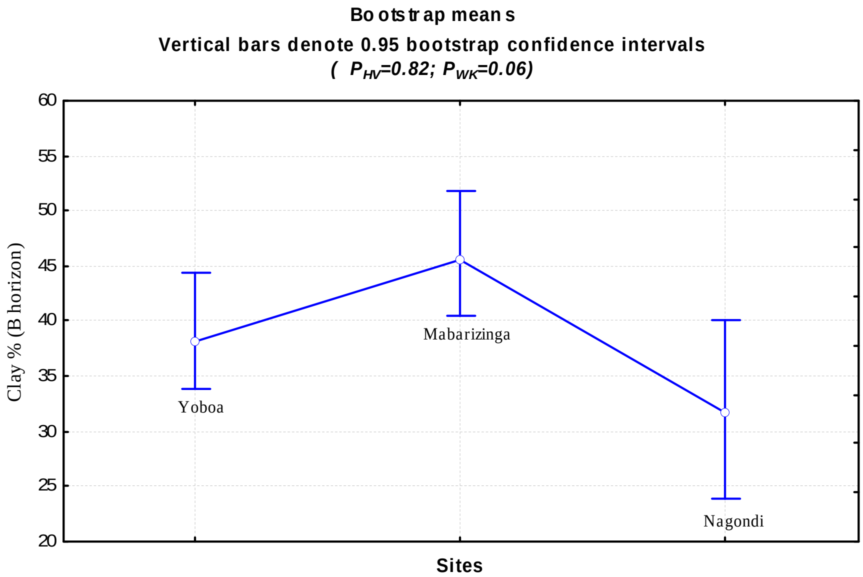
* Only gravel % in B horizon and sand % in A horizon are presented because the mean of these two variables, even though statistically not different, on these horizons only the confident interval limits (vertical bars) were different. Mabarizinga confident interval limits are for example very narrow compared to the wider of two other sites.





[*]<u>Figure 12b.</u> Statistical Comparative results of Soil clay % between sites: Yoboa, Mabarizinga and Nagondi at different horizons (A and B. The circle dots represent the sample means at each site and the vertical bars the 0.95 confident intervals for the population means.) The same alphabetic letter signifies no significance differences between the sites this at a p-value of 0.05 as all Kruskal Wallis: 0.67 and 0.06 are larger than 0.05.

[*] Only clay % in B horizon and A horizon are presented because the mean of these two variables, even though statistically not different, on these horizons only the confident interval limits (vertical bars) were different. Mabarizinga and Yoboa confident interval limits are for example very narrow compared to the wider of two other sites.

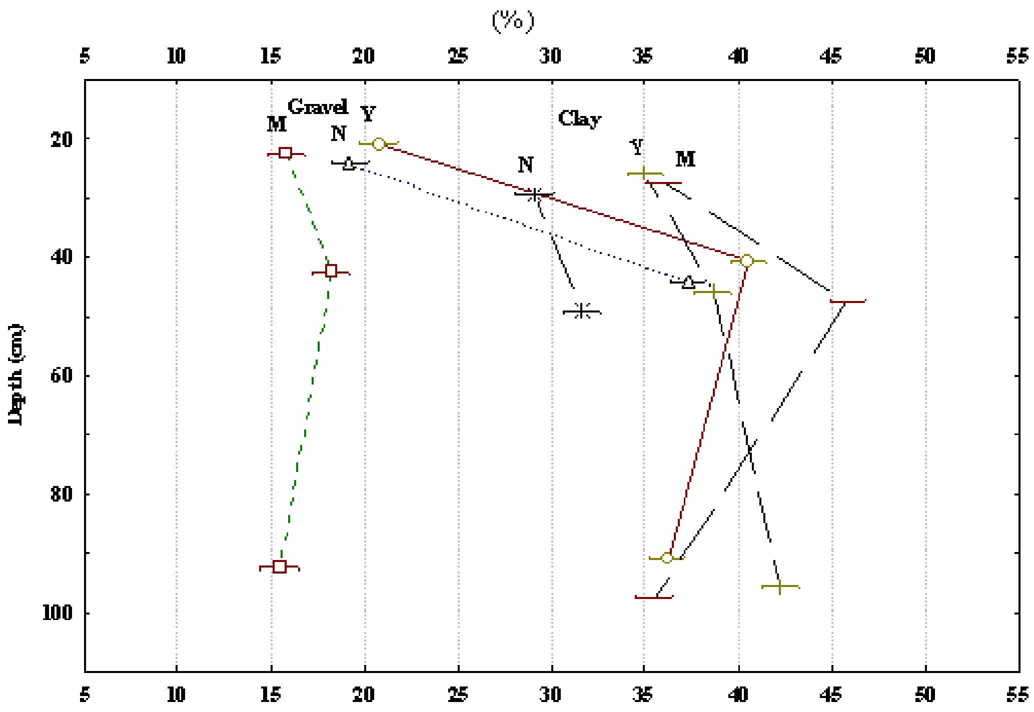


***Figure 13.* Gravel and clay % for the three sites: Mabarizinga (M), Yoboa (Y) and Nagondi (N) at different horizons: A (0-20cm), B(20-40cm) and C (80-100c)**

From **Figure 13**, the positions of the pattern means with their standard errors correspond to the profile horizons estimated on the vertical axis as a soil depth (cm). The lowest level of gravel but highest level of clay at the three sites for the A, B and C horizons is observed at the Mabarizinga (M) site then followed by the Yoboa site.

The highest level of clay content at the Mabarizinga site is reflected by its texture type of Sandy-Clay at the A (0-20 cm) and B (20-40 cm) horizons and the texture of Clay at the C(80-100 cm) horizon compared to other sites where the Sandy Clay Loam is dominant at the all the horizons (**Figure 13** and **Table 6**)**.** The general dominant texture type of Sandy-Clay-Loam (SaClLm) at the A and B horizons the Mabarizinga site in **Figure 13** and **Table 6** also show that from the top soil horizon A towards the bottom of the profile C horizon, there is a slight increase of clay proportion. Such an illuviation of the B horizon is a process through which very soluble plant nutrients such as K^{+}, Mg^{2+} and Ca^{2+} will be leached down the profile and accumulate at the subsoil with the possibility to integrate clay mineral interlayer. On the other hand, with further leaching and particularly lateral leaching these cations may be washed away resulting in a very poor nutrient soil site status as it is documented for soil under tropical rainforest. Such accumulation of clay down the B horizon is a key concept used to distinguish between family properties in some soil forms.

The dominant soil texture at the A and B horizons at each site is of Sandy Clay Loam (SaClLm). And, there is a tendency of clay accumulation deeper the soil profile. This implies that on this basis, the top soils of the three sites are suitable for teak growth. However since clay play a crucial role in water holding capacity and nutrient reserve, its occurrence at the Mabaringa and Yoboa deeper soils rate these two sites better than Nagindi for these charactristitcs.

The proximity of the Nagondi and Yobao sites to the boundary can also be used to explain the highest level of gravel at these sites at the B horizon in contrast to the Mabarizinga site further away south to the iron boundary.

The higher levels of clay at the Mabarizanga and Yoboa site might be related to their bedrock - gneiss in contrast to the Nagondi which is closer to the laterite boundary depicted on **Figure 8** (p.18). Indeed as mentioned by Herbert, Zim and Shaffer (2001), the gneiss rock although hard to define or describe because of its variety is relatively rich in feldspar or mica. Or, both feldspar and mica are documented to be the main source of clay minerals and especially that of kaolinite under excessive weathering conditions such as those in tropical climates in general and those of Nzara in particular (Trieste, 2004). The geomorphology of the area should also play a significant role in the deposit and accumulation of sediments particularly that of clay. Thus, on areas nearer the valley bottom compared to those on or midslope or footslope there should be finer material deposited. Although we did not have a geomorphological map of the study area, the Mabarizinga site is the nearest to the bottom in contrast to the two other sites. From the overview on the geological map, the Mabirizinga site appears on the complete Southern part of the study area which is also the direction where most meanders of the Nile are located.

	Yoboa			Mabarizinga			Nagondi	
Parameters	**Top soil A n = 8**	**Sub soil B n = 6**	**Deep soil C n =4**	**Top soil A n = 5**	**Sub soil B n = 5**	**Deep soil C n =2**	**Top soil A n = 5**	**Sub soil B n =5**
Gravel %	22±4	41±8	37±10	16±5	18±9	16±14	19±5	37±9
Sand %	59±4	54±4	48±15	59±6	48±5	55±18	65±6	62±5
Sand Grade	Medium	Coarse-Medium	Coarse-Medium	Medium-Coarse	Coarse-Fine	Coarse Medium	Coarse-Fine	Coarse
Silt%	6±2	8±2	10±4	5±0.4	7±2	9±5	6±2	6±2
Clay%	35±4	39±3	43±12	36±5.3	46±4	36±14	29±5	32±4
Texture	SaClLm	SaClLm	Cl	SaClLm	SaCl	LmSa Cl	SaClLm-SaCl	SaClLm-SaCl

Table 6. ***Gravel, sand, silt and clay percentage as soil sample means per horizons at each of the three sites.***

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Another interesting fact of **Table 6** is the relatively high means proportion of sand on the top (A:0-20 cm) and subsoil (B:20-40 cm) horizons. Except for the Nangondi site where the sand color was systematically white and the grains finer, the sand on the other sites was remarkably brown and dominated by medium and coarse grade. These types of brown sand so called Nubian sand have already been described in Sudan by Edwin (1963) but, the study area of that author was limited to the North around Khartoum.

The geological descriptive map given by Comboni (2003) also depicted these Nubian sand types further north of the White Nile. In the light of Edwin (1963) who claimed that the genesis of the Sudanese Nubian sand has to be an alluvial rather than a marine deposit, we are in a position to suspect the present high proportion of sand on top soils as a result of the White Nile and aeolian deposit from the North. The highest proportions of sand were encountered on the Nangondi site which is the area further north and thus closer to the White Nile flow.

Very high amount of sand (%) is observed at all two sites and land uses from all the horizons. Higher level of iron and Aluminum however are observed at Nagondi site under plantation land use. This very high level of sand and very low level of major elements can be interpreted as the result of high weathering intensity leading to the accumulation of kaolite. Under such conditions muscovite as primary mineral has less chance to resist and to be observed.

The current uniformity of the physical properties at the three sites should be taken with some reservation as it might not be a complete reflection of the reality of these soils. In the first instance, this uniformity may suggest that the weathering processes prevailing on these three sites are occurring with the same intensity and that these soils are of the same age. Although the area is generally flat, the distances between the three plantations around which soil were sampled are in the order of 10 kilometers apart from each other. At such distances, there are very little chances that the uniformity of a soil pedon will be preserved. Indeed, if the macroclimate is agreed to be the same on the entire area, the microclimate is likely to vary and affect the soil genesis.

Secondly, the Rozanov (2007) report also stipulates that the soils of this area could be formed on three main materials: the alluvium near the valley bottom, the colluvium at first terrace and residual material on the watersheds. Such a categorization of soil genesis would have led to a distinctive pattern of texture with the alluvial soils being more clayey since clay particles due to their lightness will be transported further away.

In contrast, soils of colluvial genesis should be expected to be more graveled and sandy as their finest fragments will be transported by the wind or water, thus the larger fragments will accumulate nearer the surrounding hills.

The discrepancy between these expectations and what is being currently observed here may be explained by the fact that the soil sampling was not a complete survey of the whole area but rather a sampling of selected scattered points assumed to represent the whole area. Thus, wider sampling should be planned and carried out to closer confirm the current soil uniform textures of the three sites.

In summary, the soil physical properties: gravel, sand, silt and clay of the three sites do not show any statistical significant difference. Their dominant texture is of Sandy Clay Loam type. These physical results fall within the range of other tropical countries where teak is grown as presented in **Table 2** of **Chapter I (see p. 10)**. Those resulting Oxisols are thus adequate for the purpose of the establishment of tree plantations establishment such as *Tectona grandis*. As stated by Nambiar and Brown (1997), in general Oxisols are well structured soils with a high proportion of microaggregates (0.01 to 0.2 mm size) stable to slaking due to their high levels of sesquioxides particularly that of iron and manganese.

1.2. Soil Texture and Structure Inside and Outside Teak Plantations

The disturbance of soil by land use is expected to first considerably affect soil physical characteristics such as texture and structure at least at the horizons near the soil surface. This fact has been proved in respect of intensive agriculture where heavy machinery is used. If adequate management practices are not carried out, the same fact will be true for less mechanized land use such as slash-and-burn agriculture commonly practiced in the tropical areas. Alister, Smith and Sanchez (1997) for instance found that topsoil and subsoil under uncleared forests were both sandy loams, but less than one year after clearance and burning, topsoil was modified to a clay loam and subsoil to sandy clay loam as seen in **Table 7.** Their researches in Roraima, Brazil and Amazonia also showed physical change due to disturbance of the natural soils where bulk densities increased from 1.1 to 1.5 g cm^3 after clearance. The implication of such high bulk density resulted in the reduction of soil water infiltration. However as they concluded, in areas where burning was completed within a short period of two and five years, topsoil and subsoil textures were sandy loams and that these physical characteristics have an important bearing on soil fertility and depend very much on the period of soil exposure and good management practices.

***Table 7.* Particle size analysis for topsoil and subsoil samples under different Secondary forest management: Unclear forest secondary rainforest; Previously-Cleared< 1 year; Previously-Cleared 2 years, Previously-Cleared 5 years (Adapted from Alister, Smith and Sanchez, 1997).**

Sample	Depth (cm)	>2 mm	%			
			Coarse sand	Fine sand	Silt	Clay
Secondary forest uncleared	0-5	4.22	42.72	9.61	25.5	17.95
	5-30	3.39	37.98	11.39	27.02	19.68
Cleared <1 year	0-5	5.71	29.20	5.52	17.79	41.79
	5-30	5.76	38.26	10.85	17.79	27.16
Cleared 2 years	0-15	8.30	40.55	7.52	27.47	16.07
	15-70	8.14	40.56	16.51	25.23	17.07
Cleared 5 years	0-5	9.9	45.63	7.54	18.97	17.96
	5-20	9.53	43.18	5.78	16.12	24.20

There is an accumulation of clay in top soils for a fallow period of less than a year, 17.95% from secondary forest to 41% after one year of fallow followed by a decrease under 2 years fallow period then a slight increase after 5 years: 41% to 16% and 16% to 17% after 2 and 5 years of fallow period respectively. The same is observed in subsoils: 19.68 % to 27.16 % then 27.16% to 17.96% and last 17.07% to 24.2%.

Such land use of slash and burn followed by a period of 15-35 years (Cheryl, Swift, and Woomer, 1996) is the current agriculture practice in the Southern part of Sudan where rudimentary tools for soil preparation are still in use in comparison to the more developed.

Northern part (USAID, 2004). Having pointed this out, the real meaning of soil sampled outside the plantation boundaries imply that these soils are being for the most part under different ages of fallow when they do not have any crop on them. Hence, the comparison established between the soil inside and outside plantations will be regarded as soil on fallow lands and those under teak plantations.

The comparison of soil properties means for physical properties between these outside and inside plantations did neither show any significant differences similarly to the previous grouping under sites (**Figure 13 and Table 8**). The sample means values of gravel, sand, silt and clay are almost similar to those obtained under the site' previous grouping consideration. The dominant texture types remain Sandy Clay Loam at topsoil and subsoil and Clay at some deeper soil horizons. However, in both group settings the percentage amounts of gravel and sand slightly decreases as we move down the profile while those of silt increase down the profile. Clay percentages on the other hand increase down the profile for soils outside the plantations but remain constant inside the plantation.

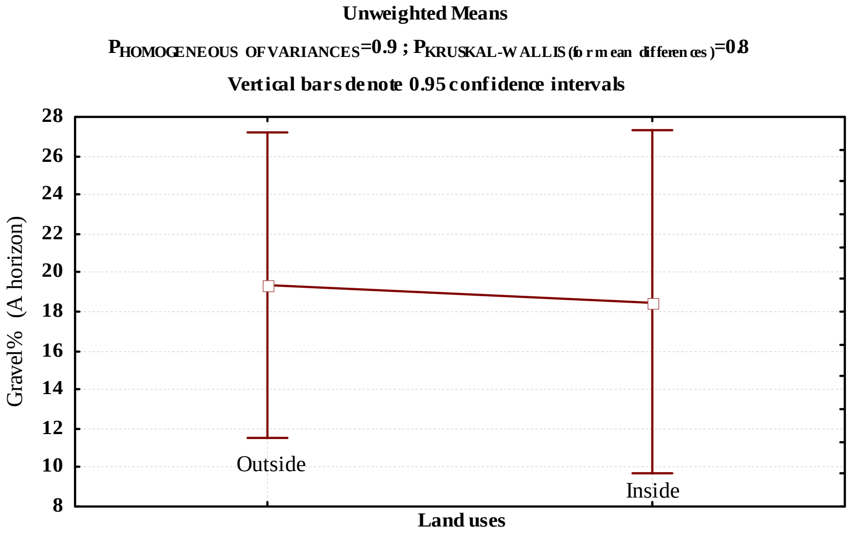
Despite the non significant statistics, differences of the means **Figure 14** and **Figure 15** show a deviation of gravel and clay. Such a difference is in agreement with the outcomes of Alister, Smith and Sanchez (1997)'s research on secondary forest in Brazilian rainforest with results in presented in **Table 7** showing a positive relationship between the accumulations of clay related to the age of the land under fallow expressed as the number of times the secondary forest was cleared for agriculture purposes. Such a difference which might not have been picked up by the analyze test for multiple similar reasons already discussed earlier, shows that there is more clay accumulation outside the plantations and more gravel accumulation inside the plantations.

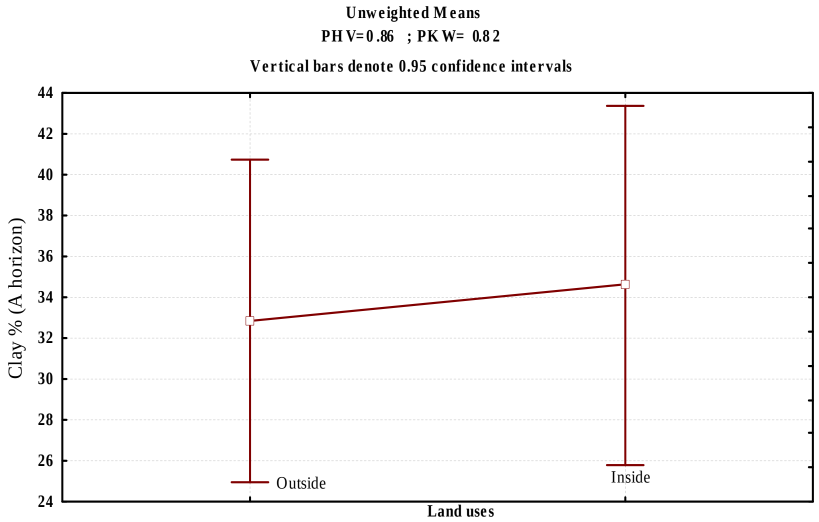
The dominant soil texture under the two land uses is also that of Sandy Clay Loam (SaClLm) on top and subsoil with accumulation of clay (Cl) down the profiles. Both land uses appear to have similar impact on soils underneath them. This is unlikely to be the case as soil cover plays a crucial role in the genesis of soil physical properties.

The accumulations of clay (%) are observed under fallow land uses on all depths and the higher amounts of gravel (%) under plantation land use, particularly in top soils. Since clay has the potential to hold cations, and gravel expresses the degree of soil erosion, soils outside plantations are less subjected to erosion and are expected to be more fertile.[*]

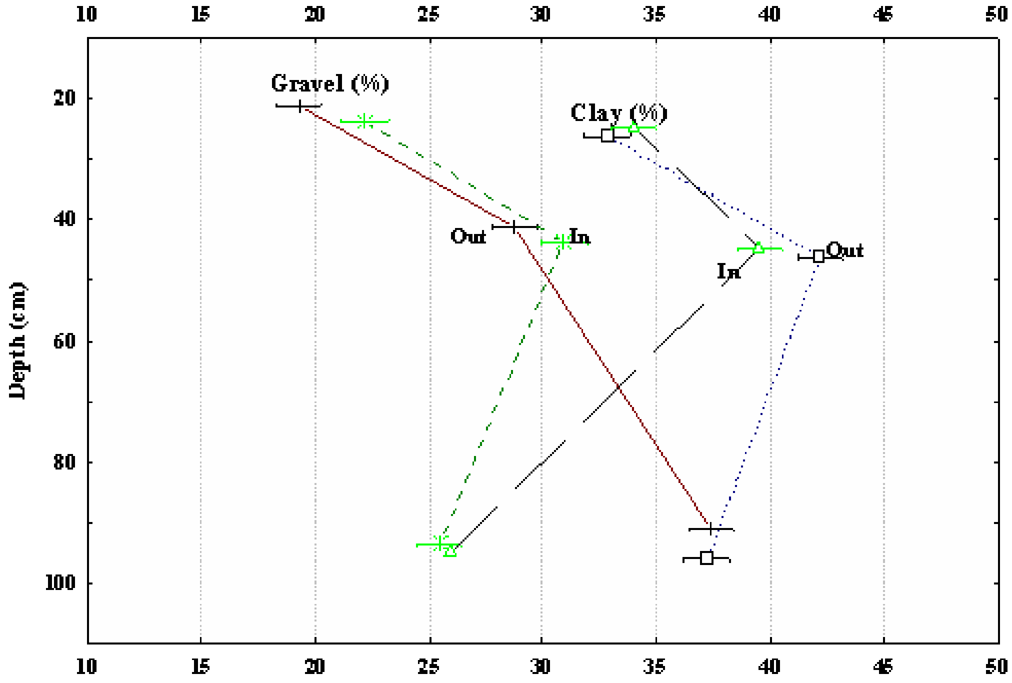
Should these differences be attributed to the effect of land uses, that is to say that forest plantations have led to a decrease of clay and an increase of gravel content through selective erosion, one would need sufficient evidence on the state of these soils before the current plantations were established on them. Moreover, since forest plantations are usually if not always established on marginal soils in order to allocate the more fertile soils to other food or cash crops, one can even argue that the main reason for which these plantations were established on these lands was principally because they were more gravelly and visibly less fertile than the others. Another reason might be that they are harder to work and further away from water.

[*] Since gravel is ferrocrete pees it could therefore also explain the old landscape.





<u>Figure 14</u>. Statistical comparative graphs of soil physical properties analyses as land use variables. The square patterns represent the sample mean for each land use and vertical bars 0.95 confidence intervals. There are no statistically significant differences for gravel% and clay% between the land uses at all different horizons since all the p-value for Kruskal Wallis: 0.8, 0.7, 0.37 and 0.82 are larger than 0.05.



<u>Figure 15</u>. Soil gravel and clay % for the two land uses: Inside "In" and Outside "Out" plantations for their different horizons: A: 0-20 cm, B: 20-40 cm and C:80-100 cm. Mean+/-SE. The crosses squares and triangles patterns represent the sample means of each physical property at the specific horizon estimated as the soil profile depth (cm).

	Outside Plantation			Inside Plantations		
Parameters	**Top soil A n =10**	**Sub soil B n = 10**	**Deep soil C n =4**	**Top soil A n = 8**	**Sub soil B n = 8**	**Deep soil C n =2**
Gravel>2mm %	19±4	33±7	31±11	19±4	33±8	25±16
Sand %	61±4	52±4	50±15	61±4	57±4	53±18
Sand Grade	Medium Coarse-	Coarse	Coarse	Medium-Coarse	Coarse	Medium
Silt%	6±1	7±1	10±4	5±2	6±2	10±5
Clay%	34±4	41±3	41±12	35±4	36±4	38±15
Texture	SaClLm	SaClLm-SaCl	Cl	SaClLm	SaClLm	Cl

Table 8. ***Summary of gravel, sand, silt and clay percentage as sample means per horizons: A(0-20cm), B(20-40cm) and C(80-100cm) and per land uses: Inside and Outside the Plantation.***

Nevertheless, it can be said that establishment of monoculture crop types will have more chances to lead to more physical deterioration of soil than would have been a more diversified crops management. This tenet makes even more sense as to agree with Pancel (1993) that establishment of forest plantations and teak in particular leads to more soil erosion where there is insufficient management to protect the soil surface through the conservation of forest understorey protecting the soil surface.

In such a situation, clay will be easily washed away through at least sheet erosion. This might be the case for South Sudan teak plantations where from **Figure 11a** it can ultimately be seen that the soil surface is completely bare not only of vegetation underneath the canopy but also bare of leaves and other falling matter expected to cover and protect the soil surface. On these images of **Figure 11a**, one can also roughly estimate the intensity of erosion affecting the soil by looking at the exposure of the tree roots at the air surface and the stability of the soil surface under the fallow lands.

In summary, the investigation of soils physical characteristics differences under the two land uses did not show any significant differences similarly to the differentiation according to site. Although we do not know for certain what were the selective criteria for the establishment of the current teak plantations which might have been among other, visual observations some 60 years ago, the fact remains that the current soils under teak plantations – though statically not proven – seem to be physically slightly more degraded than the ones outside the plantations.

2. Soil Chemical Characteristics: Acidity, Organic Carbon and Nitrogen, Exchangeable Cations, Phosphorous, Aluminum and Iron

2.1. Acidity at Different Sites: Yoboa, Mabarizinga and Nagondi

The reality of soil acidification in humid tropics areas is often mentioned as the primarily consideration in the planning of agricultural management. According to Alister Smith and Sanchez (1997), many factors that cause low crop yields in the humid tropics are associated with soil acidity which results in toxic concentrations of Aluminum. However, the Aluminum sources are diverse and complex. Here we focus on some of these factors contributing to humid tropical soils acidification and that is: rainfall or some water, parent materials and soil organic matter.

One of the main criteria used by the USDA (Soil Taxonomy); the ORSTOM (French Soil Classification System); and the FAO/UNESCO (Soil Classification System) to distinguish and classify tropical soils as Oxisols (USDA) or Ferralsols (FAO/UNESCO) is their high acidity expressed by their low pH (3 to 5). The acidity level of these soil groups is attributed to their exchangeable Aluminum cations rather than those of hydrogen as was proven by the work of Coleman and others (Sanchez, 1976). These authors argued that hydrogen ions produced by organic matter decomposition are unstable in mineral soils because they react with layer silicate clays, releasing exchangeable Aluminum and siliceous acid. According to Pancel (1993), the chemical reactions of hydrolysis under tropical high temperature and high rainfall have a more rapid effect on the weathering of primary minerals and accumulation of oxides and hydroxides of iron and Aluminum principally. Indeed, since increasing temperatures increases the dissolution of water, hydrolysis is more effective in the tropics than in the middle latitudes. The reactive mechanism of primary minerals weathering by hydrolysis is illustrated using orthoclase as an example of primary mineral:

$$^{*}KAlSi_3O_8 + HOH \rightarrow KOH + HAlSi_3O_8$$
$$HAlSi_3O_8 + 4HOH \rightarrow Al(OH)_3 + 3H_2SiO_3$$

The end products KOH, $Al(OH)_3$ and $3H_2SiO_3$ have different solubility. KOH is rapidly washed out; silicic acid as well, since in the humid tropics its solubility increases with increasing temperature. Because of this, there is in the course of geologic time spans, a relative enrichment of Al compounds in the soils, while the Si contents decrease. Both breakdown products can react with each other as long as they are in a reactive form, thereby creating secondary minerals among which kaolinite clay is the dominant type (Pancel, 1993).
Nevertheless, Dickinson, Greenfield and Roos (1989) pointed out that the effect of water on carbon dioxide produced by the decomposition of soil organic matter contributes to mainly top soil acidity status. According to these authors, water or more explicitly H^+ ions combined with carbon dioxide from organic mater decomposition forms carbonic acid which can explain the high acidic level of the top soil.

$$R\text{-}COO^- + H^+ \rightarrow R\text{-}COOH$$

* Orthoclase; adapted from (Pancel, 1993).

Since hydrogen ions produced by organic matter decomposition reacts with layers of silicate clays releasing exchangeable Aluminum, exchangeable hydrogen is thus found in small amounts in some acid mineral soils. As Perveril, Sparrow, and Reuter (1999) said, most of the soil clay minerals contain Al, but it is usually not until soil pH_w falls below 5.5 that Al is readily measurable in the soil solution and exchange sites. Below that value, exchangeable Aluminum usually becomes toxic for most plants, reduces or excludes the uptake of other plant cations such Mg^{2+}, Fe^{2+}or Ca^{2+} or form strong complexes with other anions such as PO_4^{3-} in which phosphorous becomes non available. Hartemink (2003) also mentioned that at the pH_W below 5.5, the Al becomes soluble; cation availability is decreased because the increase in protons displaces cations from the exchange sites, and the latter are subsequently leached if they are not taken up. The soil acidic level and in particular, Aluminum exchangeable saturation is thus a critical factor of soil fertility determination under tropical areas such as the present study of South Sudan.

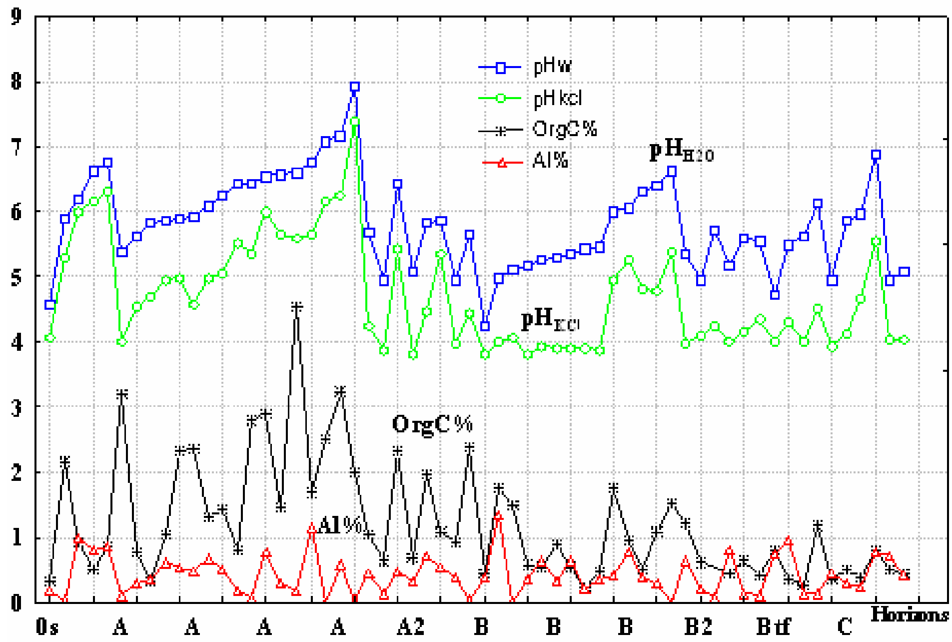


***Figure 16**. pHs measured in H_2O and KCl, organic carbon (OrgC%) and Aluminum (Al%) at the three site sites and horizons under discussion..*

The pattern regression of both pHs in water and potassium chloride (KCl), Organic carbon and Aluminum at soil horizons with all three sites included are displayed in **Figure 16**. These regressions tend to determine which of these factors, organic carbon releasing hydrogen ion (H^+) or primary mineral weathering leading to the accumulation of Aluminum hydroxide $Al(OH)_3$ is the mostly influential factor and predictable for the acidification of the soil in the area. There is a strong correlation between all factors as the variation patterns overlap each others. The organic carbon is suggested to be the factor dictating the variations of the other factors.

In overall, the ranges of pH in water (pH_{H2O}) and KCl (pH_{KCl}) were strongly correlated to each other and this can be seen through the perfect overlapping of the two representing curves of both pHs**.** As Alister Smith, and Sanchez (1997) pointed out, ΔpH calculated as $\Delta pH = pH_{H2O} - pH_{KCl}$ is a good indicator of whether soil pH is below point zero charge, i.e. pH at which the total number of positive charges equals that of negative ones and provides an accurate assessment of the nature of the net charge on the colloidal system. For example, the USDA (1999) commented that highly weathered Oxisols with high amounts of iron oxihydrates have a net positive charge (anion-exchange capacity) and that if the content of organic matter is low or negligible, in such soils, the pH_{KCl} may be higher than the $pH_{H2O.}$

The soil pH patterns overlapping in **Figure 16** imply that at all three sites and horizons, none of the pH is above point zero; all the ΔpH values are positive. This fact also reflects the net positive charge of the colloidal system and high level of organic matter at all sites. The highest means values of 6.4±0.56 and 6.16±0.7 grouped in **Table 9** were found not surprisingly on top soils (A horizons) at all the sites and it decreases as we move down the profile where the lowest values of 5.34±0.27 at the sub soils (B horizon) were observed. Those pH ranges in water particularly seem to be higher from these of the so called common Oxide-enriched soils, such as the Ferralsols which are said to be widely distributed under the tropics with pH ranges usually between 4 and 4.5 (Pancel, 1993). Those high pH ranges on the top soils are also correlated with the high organic carbon values content occurrence of 1.8±0.34, 1.92±0.43 and 1.6±0.43 against 0.89±0.16, 1.13±0.19 and 0.58±0.19 and, 0.57±0.09 and 0.44±0.12 on the top soil subsoil and deeper soil profile respectively (See **Table 9)**. The patterns of the Aluminum is however different in that the highest concentrations as percentages 0.53±0.2, 0.8±0.3 and 0.4±0.3 are found at the sub and deep soil profiles respectively while the lowest 0.27±0.11, or slightly similar to the former 0.58±0.14 and 0.43±0.14 at the top soils.

The observed pH values can be considered significantly different from the common values of 4 to 4.5 expected under tropical soils. The percentages of Al are very low in that they seldom exceed 1% and are almost constant at all profiles depths and sites. Nevertheless, the variation pattern of both pHs slightly follow that of the organic carbon. That is the lowest pHs mostly occur where the organic carbon is low. These facts show that presently, the soils of these sites have low exchangeable Aluminum and in this sense, not much Aluminum toxicity should be expected. On the basis of the above relationships between carbon content, exchangeable Aluminum and pH range values, we ought to say that the acidity of these soils are mainly influenced by the presence of the organic matter and less by the primary mineral weathering mechanisms producing Al^{3+}.

As Sanchez (1976) and Alister Smith and Sanchez (1997) says, one of the greatest advantages of soil organic matter is the strong complexes it forms with the amorphous oxides of Aluminum and iron. By forming such strong complexes, the organic matter controls these oxides concentrations and thus limits their possible toxicity to plants or inhibition of other plant nutritive elements. Furthermore, the soils of these sites might be highly weathered as any other soils in tropical areas, but the fact that the area is mostly flat and shrouded by the numerous meanders of the White Nile indicates that most of these soils have an alluvial genesis which was supported by Razonov (2007).

Parameters	Yoboa				Mabarizinga				Nangondi		
	Top soil A(0-20cm) n=8	**Sub soil B (20-40cm) n=8**	**Deep soil C(80-100+) n=3**	**Total 0-100**	**Top soil A(0-20cm) n=5**	**Sub soil B (20-40cm) n=5**	**Deep soil C (80-100) n =2**	**Total 0-100**	**Top soil A(0-20cm) n=5**	**Sub soil B (20-40cm) n=5**	**Total 0-80**
pH_{water}	6.4±0.56	5.7±0.21	5.91±0.5		6.04±0.7	5.34±0.27	5.46±0.61		6.16±0.7	5.31±0.27	
pH_{KCl}	5.37±0.3	4.43±0.19	5.88±0.93		5.14±0.38	4.17±0.25	4.33±1.4		5.03±0.39	3.96±0.25	
C%	1.8±0.34	0.89±0.16	0.57±0.09		1.92±0.43	1.13±0.19	0.44±0.12		1.6±0.43	0.58±0.19	
N%	0.11±0.02	0.069±0.01	0.05±0.01		0.11±0.03	0.08±0.01	0.036±0.01		0.1±0.03	0.05±0.02	
C/N	15.1±0.95	12.5±0.84	11.2±1.22		16.6±1.2	13.7±1.06	12.6±1.49		15.9±1.2	11.84±1.06	
$Mg^{2+}_{(cmolc/Kg)}$	0.49±0.08	0.35±0.07	0.33±0.07		0.5±0.1	0.26±0.1	0.31±0.08		0.48±0.1	0.28±0.1	
$Mg^{2+}_{(kg/ha)}$*	***611.52±100***	***546±100***	***257±55***	***1,415***	***624±125***	***406±156***	***193±50***	***1,223***	***600±125***	***437±156***	***1,037***
$Ca^{2+}_{(cmolc/Kg)}$	2.62±0.53	1.08±0.33	1.16±0.44		2.16±0.67	0.99±0.42	0.78±0.54		1.8±0.67	0.5±0.42	
$Ca^{2+}_{(kg/ha)}$	***5,450±1102***	***2,808±858***	***1,206±458***	***9,464***	***4,493±1,394***	***2,574±1,008***	***749±518***	***7,816***	***3,827±1,394***	***1,300±1,092***	***5,127***
$K^{+}_{(cmolc/Kg)}$	0.032±0.01	0.014±0.01	0.012±0.001		0.03±0.01	0.014±0.01	0.007±0.001		0.03±0.01	0.03±0.01	
$K^{+}_{(kg/ha)}$	***614±16***	***36±16***	***10.66±1***	***106.5***	***61±20.3***	***36±16***	***7.1±1***	***104***	***60±20.3***	***76±16***	***136***
Tot $K^{+}_{(cmolc/Kg)}$	0.07±0.02	0.04±0.02	0.03±0.02		0.05±0.03	0.06±0.02	0.07±0.02		0.06±0.03	1±0.02	
Tot $K^{+}_{(kg/ha)}$	***142±41***	***94±47***	***30±20***	***266***	***101±61***	***140±47***	***71±20***	***312***	***122±61***	***2,535±47***	***2,657***
$Na^{+}_{(cmolc/Kg)}$	0.029±0.002	0.03±0.001	0.03±0.001		0.03±0.002	0.03±0.002	0.03±0.002		0.03±0.002	0.03±0.002	
$CEC_{(cmolc/Kg)}$	3.18±0.6	1.47±0.39	1.5±0.48		2.7±0.76	1.3±0.49	1.13±0.59		2.4±0.77	0.84±0.49	
Avail P%	0.09±0.04	0.01±0.002	0.016±0.01		0.03±0.05	0.011±0.002	0.012±0.008		0.02±0.05	0.012±0.002	
Avail $P_{(kg/ha)}$	***4.68±2.1***	***0.6±0.13***	***0.42±0.2***	***5.7***	***1.6±2.6***	***0.7±0.1***	***0.3±0.2***	***2.6***	***1±2.6***	***0.7±0.1***	***1.7***
Tot P %	1.19±0.26	0.74±0.16	0.4±0.14		0.93±0.32	0.57±0.19	0.08±0.17		0.58±0.32	0.48±0.19	
Tot $P_{(kg/ha)}$	***62±14***	***48±7***	***10±4***	***120***	***48.4±17***	***37±12***	***2.1±4***	***88***	***30.2±17***	***31±12.4***	***61.2***
TotP/Avail P	66.7±31	83.5±18.4	23±6.7		37.7±39	58.1±22	3.48±11.54		31±39	44.23±22	
Al^{3+}%	0.27±0.11	0.53±0.2	0.48±0.2		0.58±0.14	0.8±0.3	0.47±0.2		0.43±0.14	0.4±0.3	
Al^{3+}g/kg	***0.0027***	***0.0053***	***0.0048***		***0.0058***	***0.008***	***0.0047***		***0.0043***	***0.004***	
Fe^{3+}%	1.5±0.7	3.2±0.7	2.2±0.4		3.14±0.83	1.5±1	1±0.47		1.5±0.83	1.98±1	
Fe^{3+}g/kg	***0.015***	***0.032***	***0.022***		***0.0314***	***0.015***	***0.01***		***0.015***	***0.0198***	
Fe^{3+}/Al^{3+}	***5±1.2***	***5.4±1.01***	***4.8±0.7***		***5.6±1.6***	***5±1.3***	***2.1±1***		***3.3±1.6***	***4.06±1.3***	

***Table 9*. Summary of all the sample means values of soil nutrient status at the three sites: Mabarizinga, Yoboa and Nagondi and at their profiles horizons:A:0-20cm, B:20-40cm and C:80-100cm.**

Avail P and Tot P= Available and total phosphorous respectively; Tot K^{+}= Total potassium; CEC=$\Sigma(Mg^{2+} + Ca^{2+} + K^{+} + Na^{+})$ in NH_4AOc at pH 7.

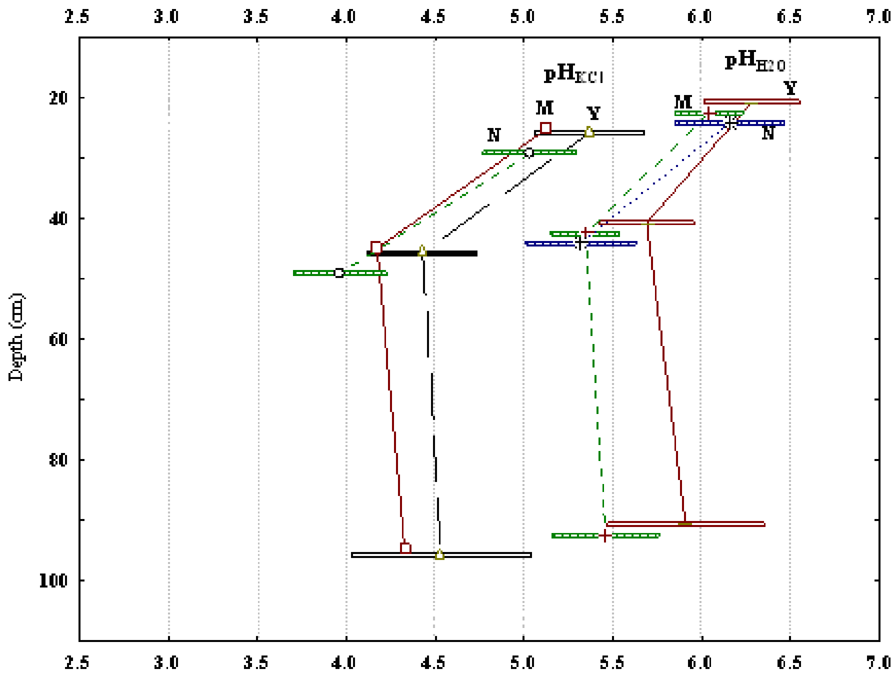


***Figure 17**. pHs measured in H_2O and KCl for all three sites (Mabarizinga:M, Yoboa:Y and Nagondi:N) at different horizons (A:0-20cm, B:20-40cm and C:80-100cm)). The squares, triangles, circles and crosses represent the sample means at site for specific horizon estimated as a soil depth (cm). Horizontal bars represent standard error of the mean.*

In these distributions of pH discussed above, the highest means values are observed at the Yoboa site. The investigation of soil clay content previously discussed shows that Yoboa is the second site of three sites with the highest range means values of clay after Mabarizinga. These high range mean values of clay and pHs may together be related to the fact that this site is the one prone to most material accumulation and, thus, younger with higher net negative colloidal charge due to more accumulation of organic matter. This higher net negative colloidal charge results in high pH range values in contrast to other sites particularly Nagondi.

To sum up, for the purpose of teak growing, in general the three sites have a high potential for teak acidity acceptance level. This is because most pHs values range between 5±0.27 to 6.5±0.8 at all sites and depths. These values are not too far from the range of 6 to 7 pHs values under which teak occurs naturally and where most plantations have since been established. Moreover, the exchangeable Aluminum acidity is not dramatically higher in profiles where it seems to occur. Of all the three sites, Yoboa appears the most suitable while the two others will be equally ranked. Subsequently, relatively low levels of P-fixation and good response to fertilization may be expected.

2.2. Acidity between Different Land Uses: Outside and Inside Plantations

Land use rather than site location may be more correlated to the chemical soil properties changes and particularly soil pH. The reasons for this is an expectation of prevalence of more negative colloidal under fallow lands and thus higher pHs value ranges in contrast to soils under forest canopy. Cheryl, Swift and Woomer (1996) for instance mention that the relatively efficient nutrient cycle of the forest ecosystem is disrupted by slash-and-burn, or any type of agriculture. The initial disruption in the cycle of natural forest is the removal of vegetation, a large aboveground reservoir of carbon and nutrients. The clearing and burning of this biomass alters the amount and timing of above- and below-ground input of nutrients from a small but continual input to a large, one-time input. The productivity of slash-and-burn agriculture is dependent on the quick release of nutrients stored in the above-ground biomass and litter burn.

The investigation results of soil acidification differences among the two land uses similar to the grouping under sites, does not show any statistical differences between the pH means at the p-value level of 0.05 as it can be seen in **Figure 18**. There is no negative ΔpH thus high net negative surface charges occur on both land uses. In both cases outside and inside plantations, the highest sample pH mean values 6.4±0.2 and 5.8±0.2 occur on the top soil A horizons and, slightly decrease towards the bottom of the profile with values of 5.5±0.2 and 5.4±0.2. In comparison with the previous grouping under sites, these samples means are similar.

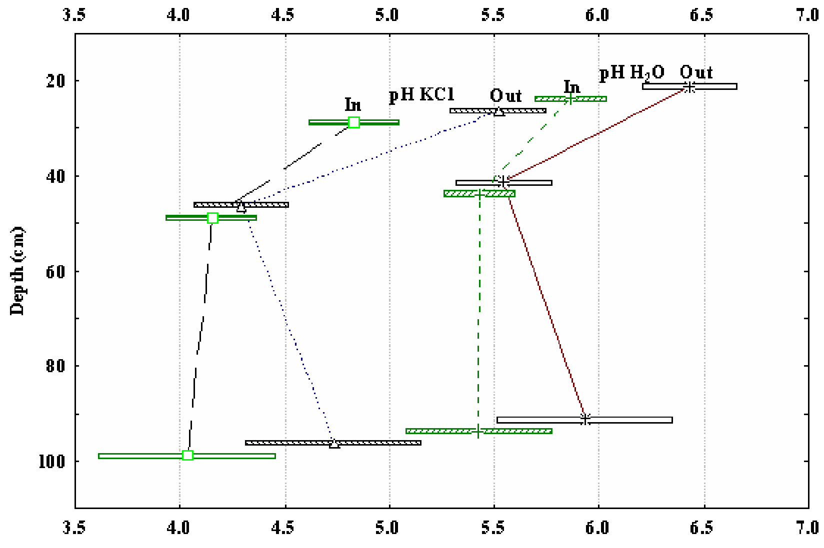


Figure 18. ***pH (measured in H_2O and KCl) between two land uses: Outside plantation "Out" and Inside "In" plantations at different horizons (A:0-20cm, B:20-40cm and C:80-100cm) estimated as the soil profile depth(cm). Mean; Box Mean+/-SE.***

The higher pH ranges in both H_2O and KCl at all depths are observed outside plantations. The soils outside plantations are thus less acidic than these inside and are expected to be subsequently more fertile.

Even though not picked up by the statistical software, there is a considerable accumulation of the organic matter on the soils outside the plantations in comparison to those inside. This alone lets one expect more amorphous oxide complexes and less Aluminum toxicity on the soil outside plantations. This is also confirmed by the fact that the lowest Al percentages in both land uses occur where the highest organic carbons are present and the highest in the B and C horizons particularly on soil samples inside the plantation. Those results are in agreement with these of Alister, Smith and Sanchez (1997) who found that Aluminum saturation is minimal under secondary forest considered to be the land under fallow.

The outcome results of high pH range values observed here in the topsoils are satisfactory for agriculture in general and teak growth in particularly. Indeed, the soil acidity of the topsoil is more detrimental to plant growth because it is the depth that sustains seedlings and also the depth at which most plant lateral roots are localized. Pancel (1993) for instance recognized that although the soil depths which should be sampled for chemical analyses depend on the main rooting zone of the species; in the humid tropics this is usually 0-30cm where about 70% of the fine roots of several common forest species are situated, as well as most (available) nutrients reserves. Drechsel, Schmall, and Zech (1990) also reported that growth and vigor of trees show considerable variations in young teak plantations in Benin (Vertisols) as well as in Liberia (Ferralsols) where differences in growth were mainly related to topsoil acidity. The high value ranges of pHs in both land uses are assumed to be strongly related to that of organic matter hence their decrease from the A to the B horizons.

In all, soils outside the teak plantations or in other words the lands under different ages of fallow have pH_{H2O} ranges values higher (6.4±0.2 for topsoil) than these of the soils (5.8±0.2 for topsoil) inside the plantations. These higher range values of pHs together with those of clay content percentage previously observed on lands outside plantations, show that the current management of plantations is not sustaining the conditions of these soils.

2.3. Organic Carbon, Nitrogen and Sum of Exchangeable Cations (S-value) at different Sites: Yoboa, Mabarizinga and Nagondi

The sustainability of a natural undisturbed ecosystem and the evergreen forest of the tropic in particularly, are governed by the turnover of the aboveground litter fall and belowground residue decomposition. Attiwill and Adams (1993) commented that nutrients are cycled from forest trees to the surface soil and litter layer in combination with large amounts of photosynthetically fixed carbon. These nutrients are then made available again for plant uptake by the processes of decomposition and mineralization, processes which have a key role in regulating nutrient availability and hence the rate of forest growth.

Cheryl, Swift and Woomer (1996) also describe that nutrients are transferred to the soil surface as litter fall, and below-ground as root litter and exudates. The litter is decomposed by the soil microflora, macro- and microfauna and converted to soil organic matter then to available nutrients. To complete the cycle, the available nutrients are taken up by the diverse and extensive plant root systems and associated mycorrhizae of the vegetation. These transfers occur throughout most of the year in humid tropical forests, the net result being an efficient release and transfer of nutrients within the system, with little loss of nutrients from the system. Nutrient additions to the system are primarily via precipitation and nitrogen fixation but can also include weathering of primary minerals.

The recycled nutritive elements if not leached away through runoff and erosion or through gaseous emissions are brought back into the cycle by plant roots uptake. These nutritive elements are present in a mixture of what is usually referred to as soil organic matter (SOM) which is the parents material of humus and comprise above ground residues litter, below ground residues (roots) and bodies of soil organisms. According to Pancel (1993), despite the lack of reliable data able to evaluate the production of belowground residues in the tropics, there are many indications that the SOM contents of tropical soils are governed less by above ground inputs, but significantly more by the belowground litter.

The supporting facts for such a conclusion emerge from climatic considerations. Indeed, the high temperatures of humid tropic create a favorable environment for micro-organisms many for whom the optima temperature is between 20 and 25°C; hence, the decomposition of litter fall is faster than in the counterpart incool temperate regions. The result is a thin layer of organic matter under the tropical forests and a deep layer under cool temperate forests Pancel (1993). This thin layer of tropical organic matter is what sustains the shifting cultivation practice in the tropics and for which a considerable period of 20 to 50 years as fallow is necessary to rebuild the soil fertility status after cultivation (Sanchez, 1976). The failure of many current slash-and-burn systems as indicated by Cheryl, Swift and Woomer (1996), is a result of the long-term uncoupling of the processes, through increased cropping and decreased fallow periods.

The estimation of soil organic matter may be derived from the organic carbon and nitrogen. The ratio between organic carbon and nitrogen is widely recognized as a good indicator of the mineralization processes prevailing in the soil and to which a certain land use can be assigned.

Dickinson, Greenfield and Roos (1989) for example, report that the carbon: nitrogen ratio in soils vary in a fairly narrow range viz 10:1 to 14:1; the wider ratios being usually found on virgin or undisturbed soils; narrower ratios on the other hand are mainly found on cultivated soils and that % Organic carbon * 1.72 = % organic matter.

The analytical results of soil chemical characteristics between the three sites are displayed in Table 10. The statistical comparison of organic carbon, nitrogen and sum of exchangeable cations (EC) in **Figure 19** shows that there is no significant difference between the means for all properties at the three sites since the p-values for test of null hypothesis that is no difference between population means were larger than 0.05.

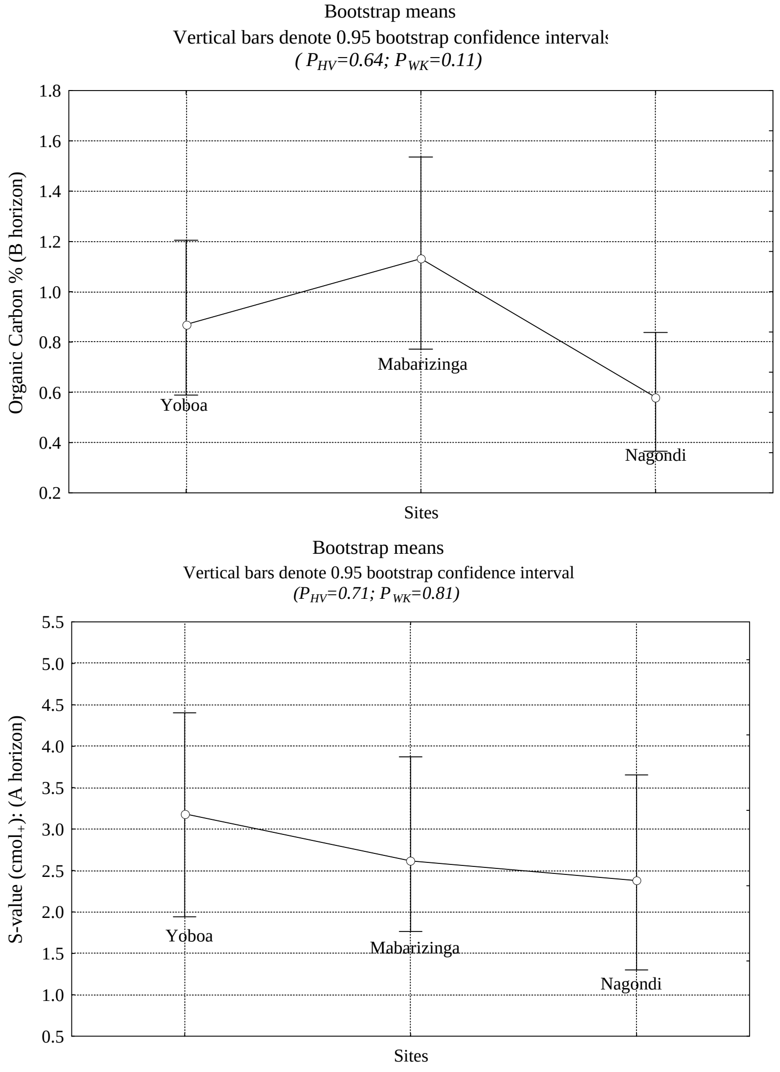


Figure 19. Results of statistical comparison of soil organic carbon, nitrogen and sum of cations (S-value: K^+, Na^+, Mg^{2+} and Ca^{2+}) between the three sites; Yoboa-Mabarizinga and Nagondi at different soil depth (A:0:20 cm) horizons. The circles represent the sample means of the organic carbon and S-value at the site and specific horizon. No statistical significant differences is found as all the Kruskas Wallis (P_{WK}) p-values are all larger than 0.05.

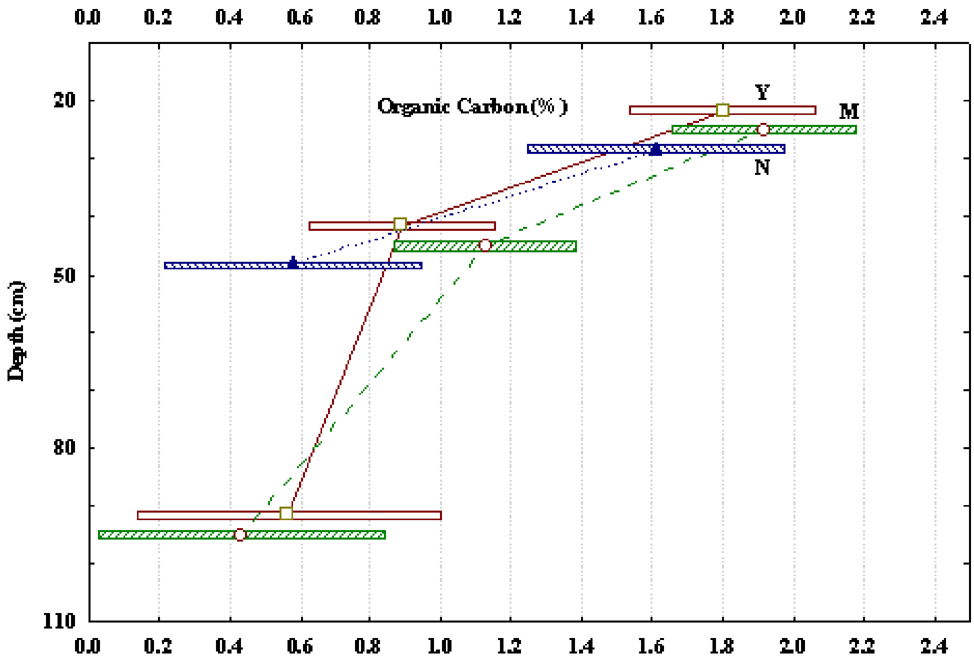


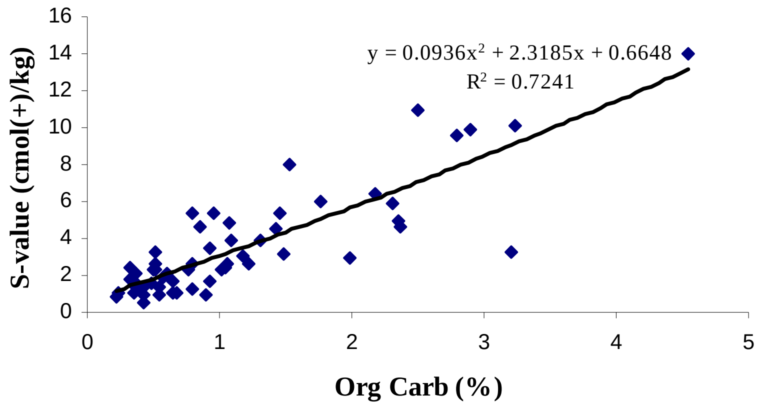
***Figure 20.* Soil organic carbon as a percentage at the three sites: Mabarizinga (M), Yoboa (Y) and Nagondi (N) for their different profile horizons (A:0-20 cm, B:20-40 cm and C:80-100 cm). The squares, triangles and circles patterns represent the sample means at each site and its specific horizon as soil profile depth (cm). The horizontal rectangles represent the standard errors of the mean at each site and its specific horizon.**

The higher values of organic carbon (%) are observed at the Yoboa followed by the Mabarizinga sites at all soil depths. This means a higher accumulation of organic matter at these sites and implies a higher fertility status at these two sites.

These statistical results also show that generally the population properties means were homogenous since the p-values for null hypothesis that there is difference between the population mean variances were also larger than 0.05. However and not surprisingly as already discussed briefly under the subtitle of acidity, the highest value of means samples for both the organic carbon 1.8±0.34, 1.92±0.43 and 1.6±0.43 and nitrogen 0.11±0.02, 0.11±0.03 and 0.1±0.03 are found at the top soils dominantly at the Mabarizinga site. These means values decrease significantly 0.89±0.16, 1.13±0.19 and 0.58±0.19 for carbon and 0.069±0.01, 0.08±0.01 and 0.05±0.02 as we go down the profile with still the highest means values at the Mabarizinga site as can also be seen on **Figure 20.**

The carbon/nitrogen ratios which follow are wider than 14:1 in all the top soils and larger than 10:1 in the other horizons. To correlate these ratios with the previous comments of Dickinson, Greenfield and Roos (1989), one might say that these sites, particularly Mabarizinga, are not much disturbed or better they were disturbed but currently have reached a certain equilibrium which lets them appear as undisturbed. Such a statement makes complete sense because the current plantations on which soil samples were collected, were planted at least some 60 years ago and the other soil samples where sampled on land generally under fallow.

Though the ages of these fallow lands are not well known they should not be less than a decade in relation to the time required to replenish the soil fertility status. The means values here observed can be admitted as a sign of soil high fertility especially for forest plantations. Indeed, Attiwill and Adams (1993) quoted that typical concentrations of organic matter in the surface soil (0-5 cm) of a highly productive eucalypt forest were 10% carbon and 0.7% nitrogen that is a C/N ratio of 14:1. These higher occurrence levels of organic carbon hence that of the organic matter in top soils also lets pre-envisage a higher level concentration of labile nutrients such as Ca^{2+} and Mg^{2+} resulting from the mineralization of organic under less weathering conditions.



<u>Figure 21.</u> Sum of cations S-value (K^+, Na^+, Mg^{2+}, and Ca^{2+}), as a centimole of charge per Kg of soil related to the soil organic carbon (%) of the three sites Mabarizinga, Yoboa and Nagondi combined: at their combined different horizons: A:0-20 cm, B:20-40 cm and C:80-100 cm.

There is a very strong positive correlation between soil organic carbon content and sum of cations. Such a correlation implies that the soil fertility of the three sites is dependent on the soil organic carbon. These values although higher than those of infertile sandy soils estimated to be 1.5 cmol(+)/kg are still low (Dickinson, Greenfield and Roos, 1989). Among multiples reasons that could explain the low S-value value ranges is the nature of clay type Koalinite dominating in the area. Indeed, Koalinite clay type are reported to have the sum of cations ranging from 5-15 cmol(+)/kg (Dickinson, Greenfield and Roos, 1989).

Since the Mabarizinga site has already shown a high occurrence of organic carbon, it could also reasonably be expected to show a higher level of sum of cations. The highest organic carbon content of the Mabarizinga site might also be related to the site topography. According to Pancel (1993), many soils testify to the influence that topography has on soil properties; concave sites generally have higher humus and nutrient reserves, as well as a higher content of plant available water, than do convex ridges or hilltops and also that it is well known that in depression and along rivers surplus water can give rise to hydromorphic soils.

The mineralization rate of soil organic matter depends in a large extent on the nature of the substrate and the type of organism decomposers. As Yuwu and Zhang (1998) said, litter fall is an important pathway for the return of dead organic matter and nutrients from plants to soil in all terrestrial ecosystems. And that the quantity and quality of litter fall can significantly influence soil biotic and abiotic environments, such as microbial population dynamics, soil nutrient dynamics, and soil moisture. Moreover, analysis of litter decomposition rates is also important for understanding nutrient cycling, energy flow, and primary production in forest ecosystems. Such an analysis of organic matter rate related to the litter fall quality and quantity can be appreciated through the relationship between carbon and nitrogen. In the current case, there is a very strong positive correlation (R^2=0.931) between the soil organic carbon content and the nitrogen as shown in **Figure 22.**

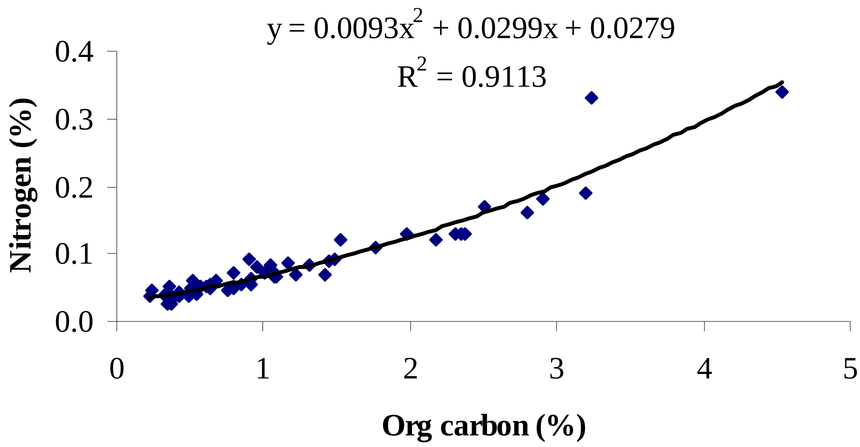


***Figure 22.* Soil organic carbon % related to the soil nitrogen content % for three sites: Mabarizinga, Yoboa and Nagondi.**

There is a very strong positive correlation (R^2=0.93) between soil organic carbon content and nitrogen at all three sites and all their horizons. The observed strong correlation of 0.93 leads to a carbon nitrogen ratio (C/N) of 15 implying a slow decomposition process of the soil organic matter (Hozelton and Murphy 2007).

Such a correlation can imply a sound uniformity or similarity of the substrate, decomposer organisms and micro-climate prevailing on the three sites. The fertility implications of such sound uniformity or similarity may be both an advantage and/or a disadvantage. An advantage in the sense that the nutrient pool can be replenished at one period after a considerable accumulation of litter fall. This can be the case at the beginning of the rainy season where under deciduous forest such as teak a considerable amount of leaves, twigs and fine roots would have accumulated during the dry season. Hence, a fast mineralization will provide sufficient nutrients for in particularly emerging seedlings and boost their growth. But it also represents a disadvantage in that if a considerable amount of nutrient has replenished the soil pool by a fast mineralization processes and it is not taken up by plants it might be leached down the profile or laterally washed away from the site through soil water erosion particularly under soils dominated by clay mineral with low cation exchange capacity such as kaolinite.

To sum up, the fertility status of the three sites is strongly correlated to the level of their soil organic carbon and thus their organic materials mineralization, as their sum of cations are positively correlated to their organic carbon. Despite the fact that the fertility status on all three sites is very low, Mabarizinga appears to be the more fertile site and Nagondi the least. Among possible explanatory reasons, the site topography and the kaolinite clay type dominance should be considered.

2.4. . Organic Carbon, Nitrogen and Sum of Exchangeable Cations (S-value) between Different Land Uses: Outside and Inside Teak Plantations

According to Attiwill and Adams (1993), investigations into the relationship between soil nutrient status and tree growth have a long history, but most dynamic, mechanistic models of nutrient uptake by trees and tree nutrition are in their infancy. An important reason for this is the sheer difficulty of the subject. Conventional chemical analyses to determine the nutritional status of the soil yield information may have little relevance in calculating the capacity of the soil to provide nutrients to trees, and the complexity of uptake processes through complex, dynamic and poorly defined root systems is tremendous.

The comparative statistical results of organic carbon, nitrogen and the sum of exchangeable cations means between the two lands uses do not show any significant difference as presented in **Figure 23** where all the Kruskas-Wallis p-values are larger than 0.05. However, there are homogeneous of variances among these soil properties at the two land uses since all the p-values for homogeneity of variances test is a also larger than 0.05. Nevertheless, the higher level ranges of organic carbon, nitrogen and sum of exchangeable cations are observed on the soils of fallow lands outside the teak plantations as shown in **Figure 24** and **Figure 25**.

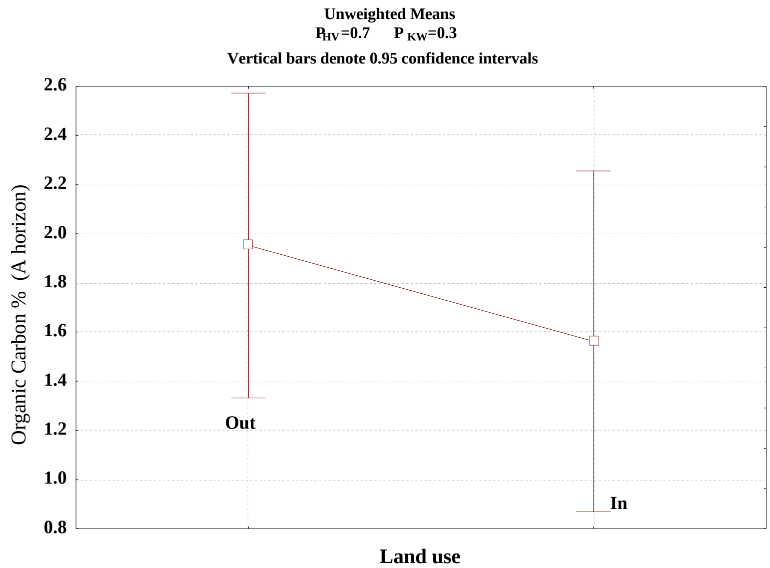


***Figure 23a*. Results of statistical comparison of the means of soil organic carbon between the two lands uses: Outside "Out" and Inside "In" plantations at specific horizon (A:0-20cm. B:20-40cm and C:80_100cm)**.

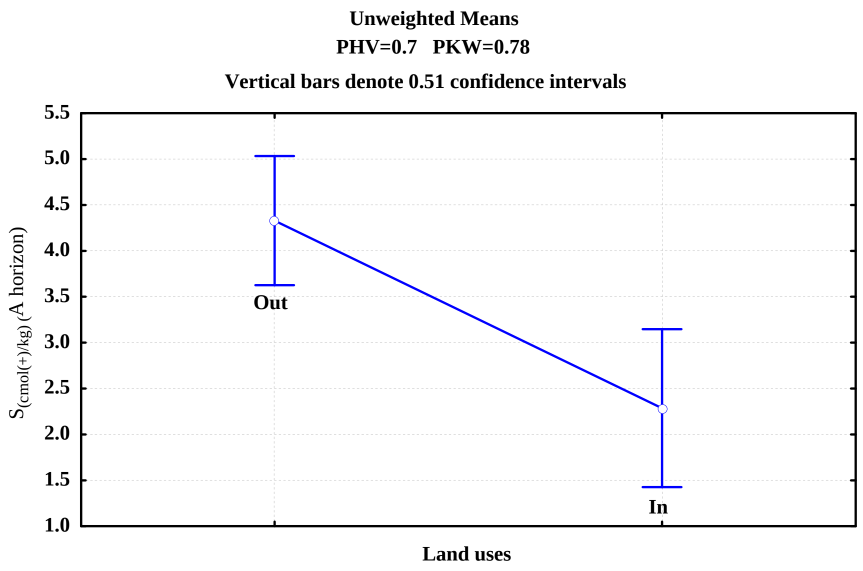


***Figure 23b*. Results of statistical comparison of the means of soil sum of exchangeable cations (S_{Value}:Mg^{2+}, Ca^{2+}, K^{+} and Na^{+}) as centi-mol charge per kg of soil ($cmol_{(+)}/kg$) between the two lands uses: Outside "Out" and Inside "In" plantations at specific horizon (A:0-20 cm. B:20-40 cm and C:80_100 cm).**

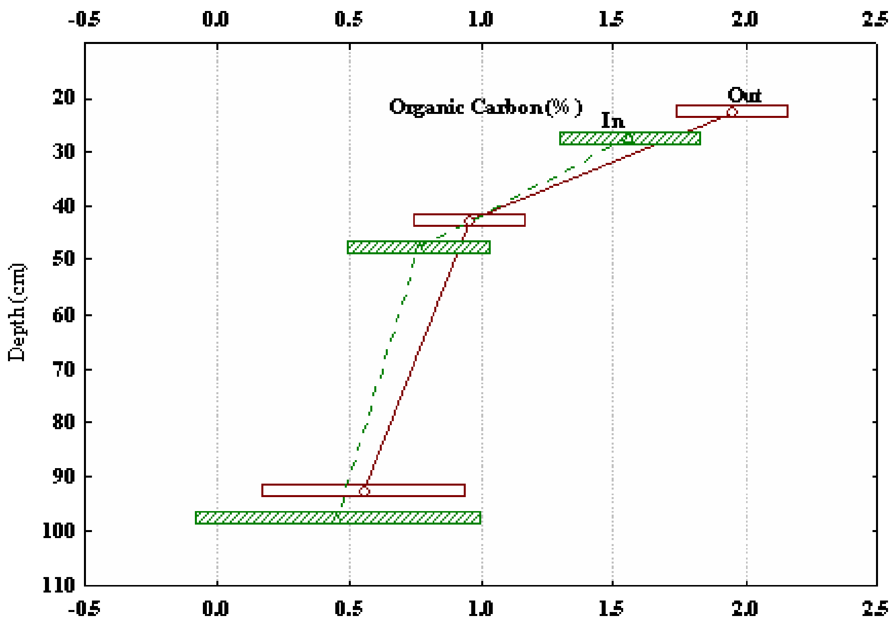


***Figure 24*. Comparison of soil organic carbon % between the two land uses: Outside "Out" and Inside "In" the plantations at different soil profile horizons: A: 0-20 cm, B:20-40 cm and C:80-100 cm. Mean; Box: Mean+/-SE. The higher accumulation of the soil organic carbon is observed on soils outside plantations. This is attributed to the vegetative richness and micro-climate favorable for decomposers prevailing on fallow lands in contrast to the barren soils inside the plantations.**

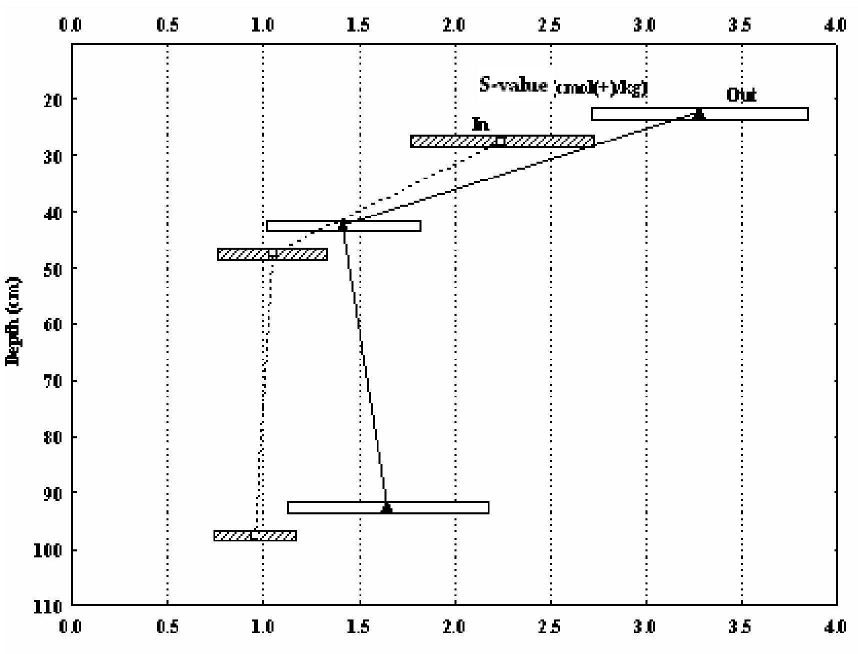


Figure 25. ***Soil sum of cations S-value (Mg^{2+}, Ca^{2+}, K^{+} and Na^{+}) as centimole charge (cmol$_{(+)}$) per Kg of soil at the two land uses: Outside "Out" and Inside "In" plantations at different soil horizons: A:0-20cm, B:20-40cm and C:80-100cm. Mean; Box: Means+/-SE.***

No significant statistical differences were noted on the 0.05 p-value as all the Kruskas Wallis (P_{KW}) p-values (0.3, 0.5 and 0.78 are larger than 0.05. However, the soil organic carbon content and the S-value mean variations are higher than those of soil inside the plantations. This implies a relatively higher fertility status of soil outside plantations. The higher concentrations of S-values are observed on the soil outside teak plantations and at all soil depths. This is the result of the higher concentration of soil organic carbon already observed on soils outside plantations in **Figure 26**.

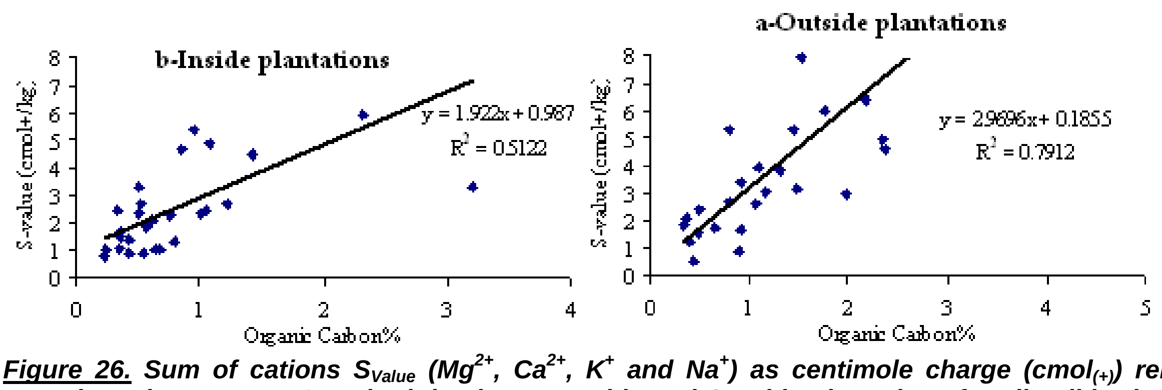


Figure 26. ***Sum of cations S_{Value} (Mg^{2+}, Ca^{2+}, K^{+} and Na^{+}) as centimole charge (cmol$_{(+)}$) related to organic carbon content % at both land uses: Inside and Outside plantations for all soil horizons.*** *The squares patterns represent individual observation.*

In both cases, there is a very strong positive correlation (R^2= 0.51 and R^2=0.79) between the S-value and the soil organic carbon content implying that the nutrient availability under both land uses depend on the level of the organic carbon accumulation and mineralization. This is particularly confirmed by the very higher correlation of the organic carbon content and S-value of soil outside plantation where more organic material is expected to accumulate.

Since soils outside teak plantations have already been observed to have higher level of clay than those inside plantations are prone to more gravel, the higher organic carbon content and S-values are no surprise. Despite the fact that sufficient evidence on the status of those soils prior to the establishment of teak is lacking to attribute the current lower organic carbon and S-value of soils inside plantations to the land use, the current lack of vegetative cover on the soils underneath the tree's canopy plays a significant role.

Indeed, as reported by Pancel (1993) tropical large forests grow in large part on kaolinitic, deeply weathered soils with very low contents of weatherable, primary minerals. Vegetation clearing either in connection with wood exploitation or for agriculture goes hand in hand with the loss of humus containing nutrients: C, N, S, P. Raymond (1996) also commented that soil erosion in teak plantations, both in Burma and India, has been confined to areas where undergrowth has been cleared and excessive burning took place. Management which maintains a protective understorey of favorable species can probably avoid both soil erosion and site deterioration under pure stands of planted teak.

In addition, heavy rains result in the loss of the top soil through erosion. The consequences are quickly decreasing soil fertility, crust formation on soil surface, accelerated soil erosion inundation, as well as a type of "savannization", since in the advanced stages of soil destruction even secondary forests cannot take a foothold. Due to the higher spread of Ferralsol under tropical rainforests such as South Sudan, Pancel (1993) recommended that more care should be taken to conserve the soil organic matter on which vegetative agriculture food and or cash crops or forest tree plantations rely for their needs.

The current nutrient differences between the two land uses might also be related to the vegetation types present in respect to both land uses. Yuwu and Zhang (1998) for example found that nutrient inputs from stemflow play an important role in differentiation of soil fertilities and vegetation composition. Stemflow is usually channeled to a relatively small area around the tree and returns a small amount of nutrients to the forest floor compared with throughfall. The natural forest on the other hand as these authors commented has a higher rate of litter decomposition and nutrient release and also larger nutrient pools in the soil than the plantation forest, which could benefit all species growing in these communities.

In essence, it seems obvious that fallow lands compared to natural forest are expected to have higher nutrient status than the uniform teak plantations. Michelsen et al (1996) also stated that the lower concentration of exchangeable cations, especially of Ca and Mg, in the planted forests, and the difference between the calculated and determined S-value both point to organic matter loss and leaching as major causes of reduced soil fertility in the plantations. Magnesium, a major element of the chlorophyll molecule and is therefore important in photosynthesis.

According to Alister, Smit and Sanchez (1997) magnesium plays an important role in P transportation within plants and movement of carbohydrates in the leaves and stems; its concentration in plants is not only affected by the amount present in the soil, but also by the concentrations of Ca and K. From the magnesium considered critical level value of 0.5 $cmol_c(+)/Kg$ (Alister, Smith and Sanchez, 1997**)** it should be expected to be deficient on the soils studied. Indeed, with the exception of the mean value of topsoil outside plantations which is just one fold above the critical value, all the other means values of magnesium are below that critical value as in **Table 14**. An application of limestone of magnesium type will thus be required to correct the existing levels.

Potassium is essential for osmotic and ionic regulation, synthesis of amino acids and proteins and to counteract the harmful effects of excessive N in plants. Trieste (2004) also reported that K deficiency directly affects crop yield since it is responsible for the maintenance of osmotic pressure and cell size, which in turn influences photosynthesis and the energy production along with stomata opening and carbon dioxide supply. But most importantly, beside carbon and nitrogen, potassium is the major element plants require in largest amounts.

According to Trieste (2004), generally, 90 to 98 percent of the total potassium in soils is in the relatively unavailable form, 1 to 10 percent in the slowly available form and about 0.1 to 2 percent in the readily available form. Alister, Smith and Sanchez (1997) stipulate that potassium critical value for crop soils ranges from 0.07±0.25 $cmol_c(+)/Kg$. Of this cut off value, only the topsoil of soils outside plantations seems acceptable with a mean value of 0.04±0.007. All the remaining range values are very far from that value. As an explanation of such low content of potassium, Alister, Smith and Sanchez (1997) suggested that layer silicates of the 1:1 type found in tropical soils do not hold cations such as K and Mg between their layers, and these are easily lost through leaching or by crop removal.

Trieste (2004) also suggests that potassium level in tropical soils occurs on the exchange complex of soils especially clayey soils; it is mobile and subject to considerable leaching particularly in sandy soils. The leaching, however, depends on the concentration of potassium in the soil solution, the amount of water moving through the soil and the ability of the soil to bind potassium. These reasons account for why the total potassium content in soils vary widely from less than 0.01% to about 4% and most commonly 1%. This might be the case in this study with as already mentioned, the dominance occurrence of Kaolinite a 1:1 clay type on the three sites. As Trieste (2004) commented, soils containing predominantly kaolinitie clay have less exchangeable potassium to release than soils that have higher percentage of illite and vermiculite clay.

These current ranges and value means of Ca, Mg and K compared to those of a teak class I in Nigeria and other West Africa countries presented in **Table 15,** show that available Ca and Mg are the only ranges closer to normal, whereas potassium is the lowest nutrient in both available and total form. A recommendation of potassium fertilizer application at least when planting seedlings will thus be of crucial importance.

Kumar, Kumar and Fisher (1998) for instance found in the management practice of intercropping teak with *Leuceana* in Kerela, that increasing relative proportions of *Leucaena* in the mixture with teak had a consistently favorable effect on both height and radial growth of teak saplings at 3–4 years of age; And thus using N_2 fixing trees could therefore, be a viable silvicultural option for stimulating teak growth, especially on infertile sites. Zanin (2005) also acknowledged and urged that teak tree prunings must be recommended in a sequence that the first pruning should take place between ages two and three when the majority of trees reach five meters in height and have a diameter of six centimeters. On average, half of the total height of the tree should be pruned. Anything more can damage the total photosynthetic capacity and, consequently, growth will slow. The second pruning should take place in the fifth year or when the trees reach ten meters in height and the last pruning should remove 60% of the total height when a tree reaches twelve meters or seven years.

In all, the organic matter on which tropical soils nutrient fertility relies is in general higher in the soils outside the plantations than these inside the plantations. Of all the soil nutrients, available elements investigated under these two lands uses types; potassium and magnesium will require a particular attention of supply and management. In essence, slow release and less soluble potassium rich fertilizer such as Potassium magnesium sulfate (K_2SO_4;$MgSO_4$ or (K, Mg)SO_4)) in a granular form is advisable at planting in applying such fertilizers. High calcium concentration is for example reported (Alister, Smith and Sanchez 1997) to possibly induce potassium deficiency and high potassium concentration can cause magnesium deficiency in plants. But moreover, further management intended to restore and/or maintain the understorey of particularly legumes should be carried on through planting herbaceous vegetations to reduce the erosion intensity and also through proper planned pruning and thinning operations.

2.5. . Available and Total Phosphorous, Iron and Aluminum between Sites: Yoboa-Mabarizinga and Nagondi.

Trees as perennial crops possess deep rooting systems which enable them to explore soil depths where annual crops with their shallow roots cannot reach, trees and hence forest plantations growth also rely on soil nutrient reserves after canopy closure rather than on available and quick recycling nutrients only. As said Young (1976) trees rely on slowly releasing nutrients from resistant primary minerals such as muscovite and nutrients trapped between layers of reconstitute secondary minerals such as Kaolinites. The evaluation of soil index total nutrient concentrations, rather than exchangeable only is justified to better estimate the long term sustainability of the plantation stands nutritional levels. Such a concept is particularly essential when it comes to major elements K and P which according to Pancel (1993), are in excess demand from the atmospheric inputs under older undisturbed forest plantations whereas the N demand is nearly in balance under the same conditions.

The effect of Aluminum is of great concern in tropical soils. Indeed, despite its toxicity that causes defect in plant cell division, decrease of roots respiration and interferences with uptake and transport of essential plant nutrients; it is its complexation with phosphorus P that becomes unavailable to plants that is of most concern in regard to agriculture. Similar to the other nutrients as previously discussed, phosphorous in this study is also positively related to the soil organic carbon as seen in **Figure 27**.

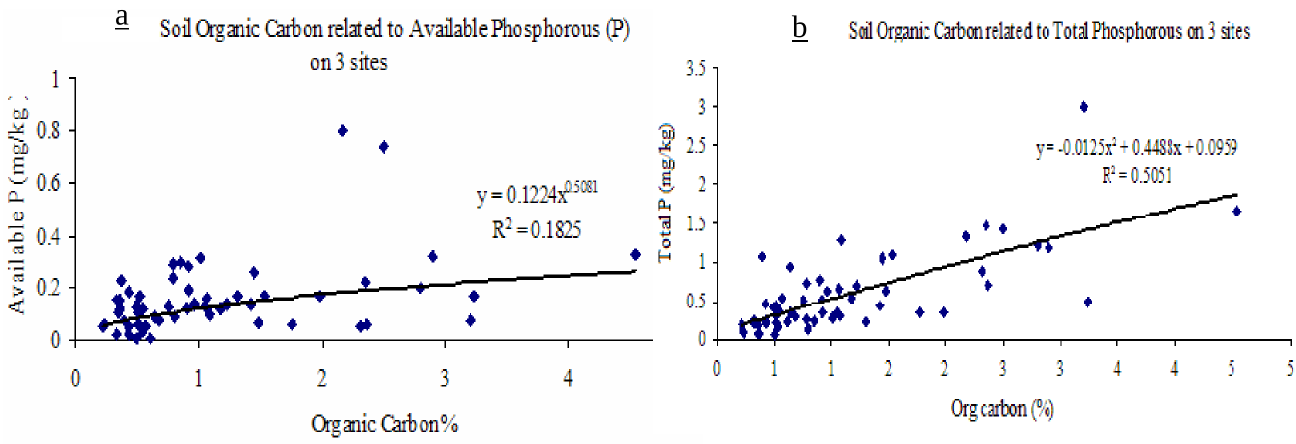


Figure 27a and 27b. ***Soil available and total phosphorous as mg per kg of soil (mg/kg) at the three sites: Mabarizinga, Yoboa and Nagondi with all the soil profile horizons: A:0-20 cm, B:20-40 and C:80-100 cm) combined related to soil carbon content %. The squared patterns represent individual observation.***

There is a weak positive correlation (R^2=0.2) between both factors. This implies that the soil organic carbon is the main resource of available phosphorous on the three sites. The range values are however very low due to maybe P sorption or P low concentration from the organic matter mineralized or both altogether.

There is a strong positive correlation (R^2=0.51) between both factors as seen in **Figure 27b**. This implies that the soil organic carbon is the main resource of total phosphorous on the three sites. The contribution of iron and Aluminum as decomplexation input from soil P sorption is thus negligible compared to the contribution of soil organic carbon content as suggested in **Figure 27a**.

This finding confirms the results of Alister, Smith and Sanchez (1997**)** who concluded that organic carbon was not only an important source for N and P and put the soils of their study area in a very low fertility status with respect to these nutrients but moreover, organic matter controlled the concentration of Al which plays an important role in creating soil acidity and is also a growth-limiting factor for plants.

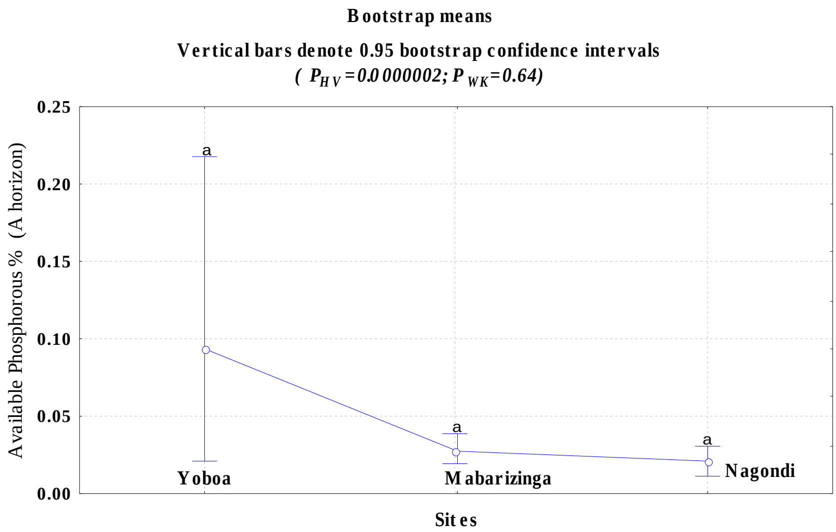
Despite no statistical difference between means of the available and total phosphorus on the three sites as shown in **Figure 28,** there is a substantial difference between the two estimated indexes of phosphorus. This difference is appreciated in **Figure 29.**

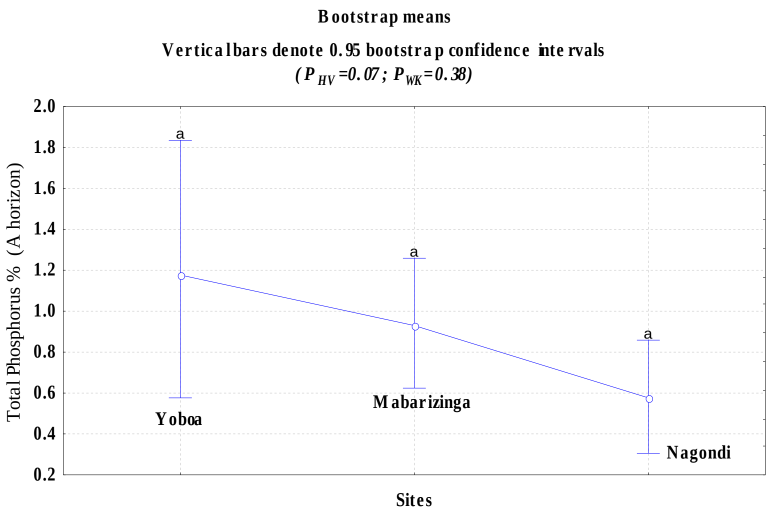
The values of both available and total phosphorous are generally very low when compared with those obtained by Bationo, Job, Vanlauwe, Waswa and Kimetu (2005) presented in **Table 10**. These authors attributed such low values of phosphorous to the low soil organic matter content due to the low shoot and root growth of crops and natural vegetation and the rapid turnover rates of organic material as a result of high soil temperatures and fauna activity particularly termites and also the low soil clay content with kaolinite as the main clay type.

	pH (H_2O)	Organic Carbon (%)	Total N (%)	Total P (%)
Equatorial forest	5.3	2.45	0.16	0.063
Guinea savanna	5.7	1.17	0.14	0.039
Sudan savanna	6.8	0.33	0.049	0.029

***Table 10.* Carbon storage and other fertility indications of granitic soils in different agro-ecological zones in West Africa (Adapted from these Bationo, Job, Vanlauwe, Waswa and Kimetu, 2005).**

The acidic soils (lowest pH_{H2O} :5.3 and 5.7) here are the ones presenting the higher fertility status (higher organic carbon, nitrogen and total phosphorous under Equatorial forest of West Africa zone contrasted with the neutral soils of Sudan savanna representing a very low fertility status. This means that higher soil pHs does not necessary imply higher soil fertility status but rather the organic carbon soil content.

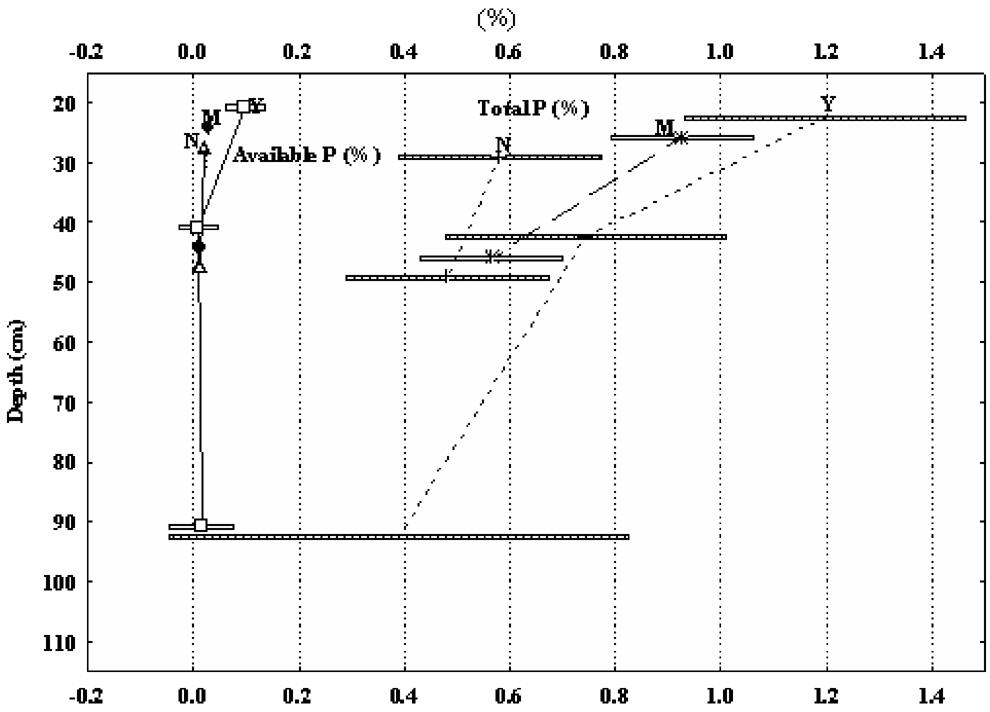




<u>Figure 28</u>. statistical comparative results of available and total phosphorus as mg of P per kg of soil (mg/kg) between the three sites: Mabarizinga,Yoboa and Nagondi at different soil profile horizons: A:0-20cm. The square patterns represent the sample means and the vertical bars represent the 0.95 confident interval of the mean.

There are no significant differences of the available and total P between all the sites at concerned horizons as all the Kruskas Wallis p-values (0.6 and 0.3) are larger than 0.05. The higher means variations of both available and total P are observed on the topsoils (A horizon) at the Yoboa and Mabarizinga sites implying a substantial input of P fromthese sites organic carbon content.

Of the three sites, Yoboa has the highest value ranges of both available and total phosphorous whereas Nagondi has the lowest of both as shown in **Figure 29**. Once more, because of the phosphorous correlation with soils organic carbon content, these results are in agreements with the previous investigation of organic carbon content between sites and where Mabarizinga is followed second by Yoboa revealed the highest level values. This is also confirmed by the fact that the level amount of the total phosphorous on the three sites decreases with depth, reflecting a decrease in the level of organic carbon of organic matter. The soil geological map also depicts Nagondi closer to the concreted iron layer in comparison to Yoboa and Mabarizinga. Such a localization of Nagondi may also imply that in overall there is very few inorganic phosphorous in these soils which would otherwise been higher for the total phosphorous at the Nagondi sites, the closest to iron concreted layer. Most phosphorous in these soils rather is in organic form and controlled by the organic matter.



<u>Figure 29</u>. Soil available and total phosphorous (P) as mg of P per kg of soil at the three sites: Mabarizinga (M), Yoboa (Y) and Nagondi (N) and at their specific horizons: A:0-20cm, B:20-40 and C:80-100cm. The circles, squares, triangles and crosses pattern represent the sample means of P. The horizontal rectangle bars represent the standard error of the mean.

The higher concentrations of phosphorous both available and total are observed at the Yoboa and Mabarizinga sites for all soil profile depths. These results once more lead to the consideration of both these sites as the most fertile of the three.

As already mentioned earlier when discussing the processes of exchangeable Aluminum, the formation of clay minerals results from the weathering of primary minerals. Under humid tropics, the intensive chemical weathering of basic rocks causes high wash-out rates of Ca, Mg, K, Na and Si while the soil becomes enriched with Aluminum and iron compounds. As stated by Agbenin (2003), this enrichment of iron and Aluminum compound has become the pedological feature of most tropical soils where the nature and abundance of free Fe oxides may be mobilized and deposited in soil profiles as iron mottles, concretions and hardpans.

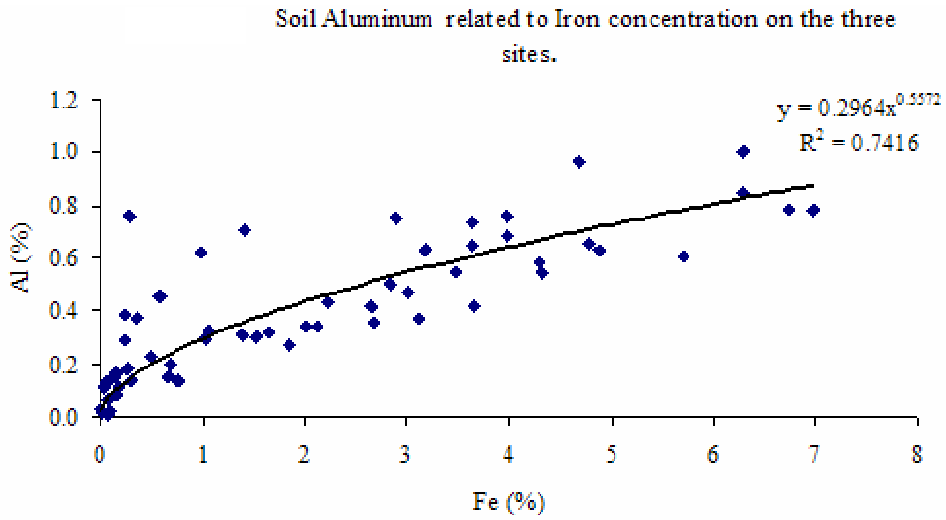
Agbenin (2003) commented that free iron (Fe) oxides in soils are rarely pure because the central Fe^{3+} ions are easily replaced by Al^{3+} present in the same pedoenvironment where free Fe oxides are formed especially in weathered soils where the degree of substitution of Al^{3+} for Fe^{3+} in clay minerals may have reached its maximum extent. The nature but, mostly the abundance of soil iron (Fe) free oxides can be estimated by using the Dithionite Citrate Bicarbonate (CBD) extraction procedure.

Attiwill and Adams (1993) remarked that Citrate is commonly used as an extractant for soil phosphorus since it replaces phosphate on the adsorption complex. Furthermore, iron and Aluminum from iron and aluminium phosphates form stable chelates with citrate and malate, freeing the phosphate for uptake. Agbenin (2003) also commented that the acid ammonium oxalate extracts poorly crystalline and amorphous Fe (Fe_2O_3: Fe_o) and Al (Al_2O_3: Al_o) oxides whereas the Dithionite Citrate Bicarbonate is used for extraction of both crystalline and non crystalline Fe (Fe_2O_3: Fe_d) and Al (Al_2O_3: Al_d) oxides. The particular characteristic of Fe_d and Al_d oxides relies on the fact that in crystalline iron oxides such as goethite and hematite highly present under the tropics, Al_d is thought to be substituted by Fe_d in the soil phyllosilicate minerals. The effect of such substitution is the structural distortion of crystalline iron oxides with implication of anions such as the orthophosphate PO_4^{3-} retention and surface area reaction. From this fact Dawit, Johannes, Lehmann, Fritzsche and Zech (2000) quoted that phosphorus (P) is among the most limiting nutrients for food production in the sub-humid and humid tropical highlands of East Africa and this deficiency is mainly caused either by the inherent characteristics of the parent material or by the strong sorption of PO_4^{3-} to Al and Fe-(hydr).oxides, which turns large proportions of total soil P into unavailable forms.

The ratio Fe_o/Fe_d is usually used to give indication of the degree of crystalline of Fe oxides in soils. Low ratio indicates a high degree of crystalline thus, high Al_d substitution, high structural distortion and hence high phosphorous and other anions retention (Agbenin, 2003). However, since we did not do any Fe ammonium oxalate extraction to determine Fe_o and hence the ratio Fe_o/Fe_d, this comment simply serves as a guide for future alternatives in the investigation of iron degree of crystallinisation.

The soil weathering intensity can however be appreciated by its end products which in this case are principally iron (Fe) and Aluminum (Al). The strong positive correlation (R^2=0.7) between Al_d and Fe_d (crystalline and non crystalline) shown in **Figure 30** can be used as an appreciation of the current soils weathering intensity.

The correlation indicates the proportionate degree of weathering intensity from which these Al and Fe are released but also, a certain intensity level of crystalinity prevailing between Aluminum and iron in soil minerals particularly phyllosicate clay minerals structures where both elements are interchangeable. An attempt to correlate the presently observed soil total phosphorous with Al and/or Fe did not show any pattern correlated to any of the two as this would have explained the low level of P by its complexes formed with these Al and Fe hydro-oxides or crystallines. Such a non correlation simply confirms the fact that even the total level amount of P in this case here is also relying on the organic carbon level and very few if any is in inorganic form from Al and Fe hydro-oxides or crystalline decomplexation.



[1]***Figure 30**. Soil Iron (Fe%) and Aluminum (Al%) content of the three sites: Mabarizinga (M), Yoboa (Y) and Nagondi (N) and at specific horizons: A:0-20 cm, B:20-40 and C:80-100 cm all combined*.

There is a very strong positive correlation (R^2=0.7) between the Fe and Al. This suggests similar weathering intensity of primary minerals or bedrocks occurring on the three sites. Weathering from which Fe and Al are thus the final products.

Since the Al_d in the phyllosilicate layers is acknowledged to be replaced by Fe_d, the level amount of Fe_d should play a determinant role in the possible substitution intensity degree of Al_d. and thus a good indicator of the soil phosphate sorption index. Therefore, a comparison between the level amounts of Fe_d found by Agbenin (2003) for the soils phosphate sorption indexes in **Table 11** and those of the current study will give an approximate indication of the current sites soils phosphate sorption indices for the possible inorganic crystalline P forms.

[1] Al and Fe content were expressed in % and not as cmol+/kg because the organic carbon, nitrogen and phosphorous they are intended to affect on were expressed as %.

Although the means of Fe_d/Al_d ratios were both similar at surface and subsurface and equal to 7 as shown in **Table 11**, the remarkable difference lies in the high level of Fe_d more correlated to the rate increase of phosphate sorption index. Indeed, as said Agbenin (2003) a regression of P sorbed on Fe_d indicates that 71% of the variance in P sorbed or P sorption index was explained by Fe_d. Despite the non statistical differences noticed between means of Al and Fe at the three sites, the sample means show that the higher phosphate sorption indexes occur on the Yoboa site and at the subsurface soil horizons where the higher means of Fe_d were observed as shown in **Figure 31**.

Horizon	**pH ($CaCl_2$)**	**Fe_d (g/kg)**	**Al_d (g/kg)**	**Fe_d/Al_d**	**Al-subst mol%**	**P sorbed**		**Phosphate sorption Index**
						mg/kg	**% of applied**	
Surface	5.1	**4.4**	0.57	7.7	13	120	8	**82**
Surface	4.7	**4.3**	0.67	6.4	18	103	6	**73**
Surface	5	**6.3**	0.82	7.6	19	165	10	**77**
Surface	5	**6.1**	0.87	7	19	137	9	**63**
Surface	4.8	**4.2**	0.62	6.7	19	107	7	**68**
Surface	4.9	**4.1**	0.57	7.2	17	146	9	**59**
Surface	5.3	**4.7**	0.57	8.2	17	236	15	**109**
Surface	5.3	**5.6**	0.67	8.4	17	127	9	**68**
Mean	***5.02±0.2***	***5±0.7***	***0.7±0.2***	***7±0.6***	***17.4±1.5***	***143±3***	***9±2***	***75±2***
Subsurface	5.3	**11.1**	2.04	5.4	21	268	17	**102**
Subsurface	5.6	**10.7**	2.31	4.6	24	384	24	**220**
Subsurface	4.7	**11.3**	2.14	5.3	22	386	24	**209**
Subsurface	4.6	**10.9**	2	5.5	23	460	29	**224**
Subsurface	4.5	**9.9**	2	5	29	460	29	**224**
Subsurface	4.6	**12**	1.82	6.6	20	423	27	**205**
Subsurface	5.6	**6**	0.86	7	18	212	13	**99**
Subsurface	4.9	**5.2**	0.62	8.4	14	188	12	**87**
Subsurface	4.7	**5.8**	0.53	11	11	165	10	**76**
Mean	***4.9±0.1***	***9±0.7***	***1.6±0.2***	***7±0.5***	***20.2±1.4***	***237±30***	***21±2***	***161±2***

***Table 11.* Dithionite-extractable Aluminum (Al_d), iron (Fe_d) and phosphorous (P) sorption capacity of the surface and subsurface soils of the northern Guinea of Nigeria (Adapted and modified from Agbenin, 2003).**

With similar ratio of Fe_d/Al_d (here 7) at different soil depths (here surface and subsurface) the Al substitution capacity and thus phosphorous sorption is conditioned by the levels of Fe_d and Al_d: the higher these concentrations are, the higher the amount of phosphorous sorbed. Here the mean 5 and 0.7 compared to 9 and 1.6 led to phosphorous sorption of 143 and 237 Kg on surface and subsurface respectively.

The concentration level of extracted Citrate-Bicarbonate-Dithionate (CBD) Aluminum (Al_d) and Iron (Fe_d) obtained on the soil of the three sites: Mabarizinga (M), Yoboa (Y) and Nagondi (N) shown in **Figure 31** are relatively similar to those of Agbenin (2003) in **Table 11** where the higher P sorption indexes (161±17) were observed at the subsurface with value of Al_d of 1.6±0.2 g/kg. Despite the no correlation existence between Al, Fe and total P, the highest levels amounts of Fe, with the exception of the Mabarizinga site, occur at subsoil horizons (**Figure 31**). In contrast and surprisingly, the total P high levels were observed on the topsoils (**Figure 31**). In both cases the highest value ranges of iron and total P were observed at the Yoboa sites.

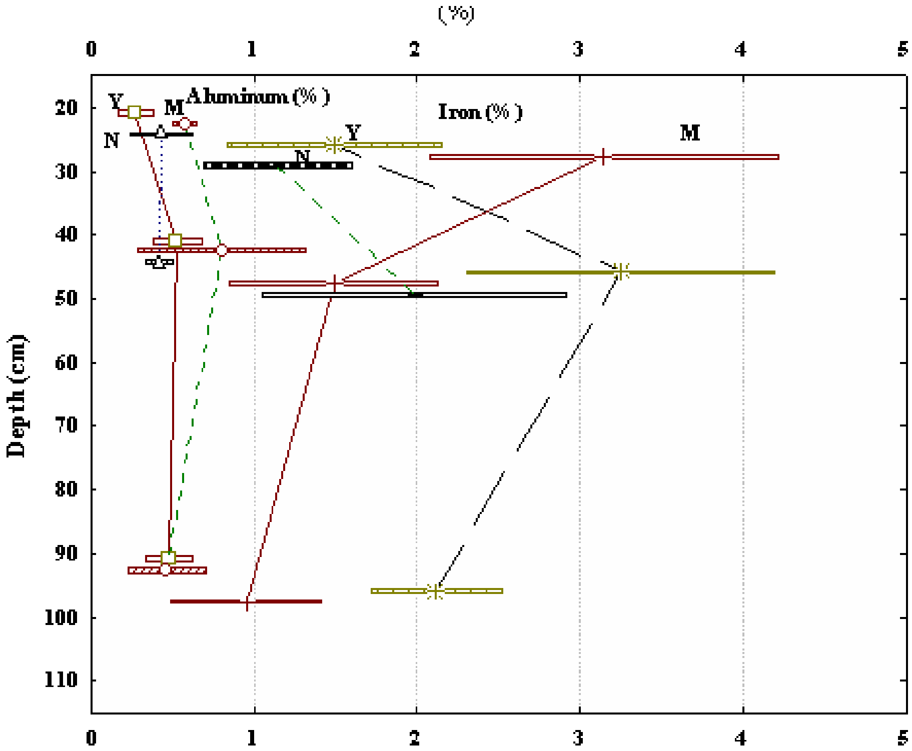


Figure 31. ***Soil Dithionate extractable Aluminum (Al%) and Iron (Fe%) for the three sites: Mabarizinga (M), Yoboa (Y) and Nagondi (N) at different horizons: A:0-20 cm, B:20-40 and C:80-100 cm. The circles, triangles, squares and crosses represent the sample means on each site at the specific considered horizon. The Horizontal rectangle bars represent the standard error of the mean.***

The reasons for this may be found in the site high level of organic carbon as being the second fertile site after the Mabarizinga, its proximity to the iron concrete layer depicting boundaries on the geological map but also that site landscape. As remarked Bourgeon and Gunnell (1998), the striking differences in tropical soil surface color are a true signature of landscape: deep red soils governed by high hematite/goethite ratio dominate in India whereas ochre tints, indicating the dominance of goethite prevail in Sudano-Sahalian Africa. Such a dominance of goethite also implies that rainfall is both low enough to prevent total hydrolysis of rock minerals but sufficient to produce free iron from partial weathering of these minerals.

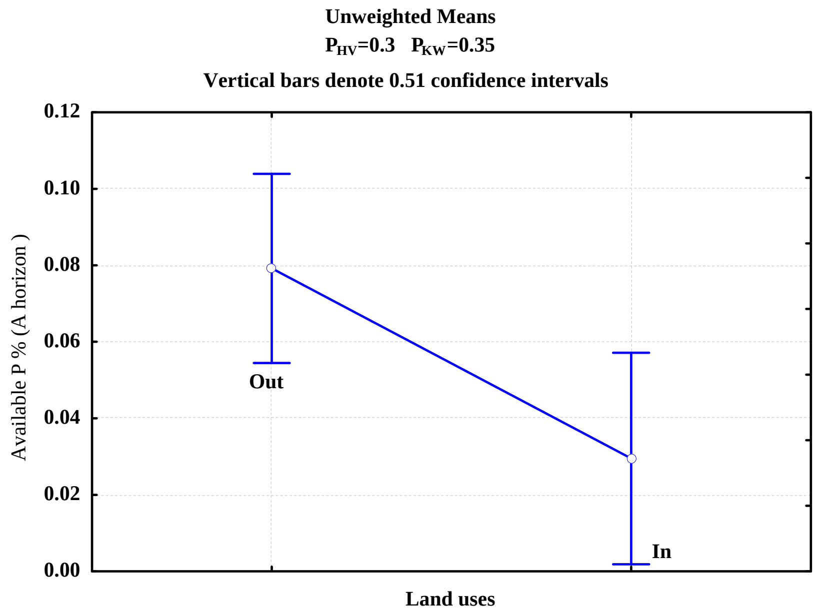
Topsoils of Mabarizinga and Yoboa sites have the higher concentrations of iron. At the subsoil, Mabarizinga has the lowest iron concentration and the iron level of Yoboa significantly decreases. A pattern which may imply that the iron boundary depicted on the geological map is not as accurate as it appears because Nagondi is expected to have the highest iron concentration due to its closeness to the iron boundary. The variation of Al follows that of Fe which is observed at Mabrizinga where the topsoil level of Al is also higher. Such a variation of Al in regards to Fe is not surprising as a positive strong correlation has already found between the two variables.

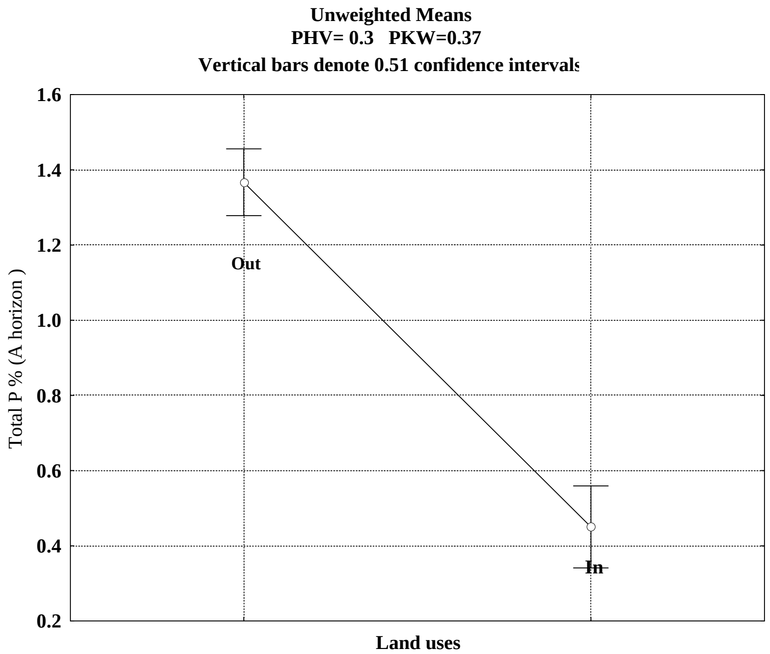
The strong correlation between Fe_d and Al_d is also reflected by the mottles and hardpans observed at the near surface of some soil profiles on the three sites and where the soil family Nomanci and Dresden which are very shallow were localized. The low P sorption index might also be the result of the goethite iron type dominated in the area rather than hematite.

Since the means of Fe_d/Al_d in Table 9 are in general 1.4 fold these of Table 12, a quantitative approximation of P sorption from that Table 12 related to the current soils can be approximated as $(\frac{237}{1.4}=169)$ 169±21 mg/kg for the topsoils and $(\frac{143}{1.4}=102)$ 102±23mg/kg of soil for subsoils of the three sites. That is 1kg of soil will require 169±21 mg and 102±23 mg of phosphorous fertilizer for the top and subsoil respectively and under condition of minimum erosion. According to the phosphorous sorption index definition given by Agbenin (2003) it is the amount of P sorbed from a P application of 50mml/kg soil (1.6g/kg soil) of phosphate (PO_4^{3-}) which is a type of highly pure phosphorous. The observed above values of 169mg and 102mg on top and subsoils respectively indicate an expectation of low P sorption indices when considering the sorption index definition given by Agbenin (2003).

In terms of fertilizer recommendation, as Pancel (1999) put it soil analyses without fertilization trials is not able to provide quantitative estimates of nutrient requirements and fertilizer applications. Nevertheless, in the absence of field trials, the alternative for fertilizer recommendations is the use of experiences from comparably similar projects species and sites. For the specific case of tropical forest plantations, one has to bear in mind that most tropical soils have a very low cation absorption capacity as is the case with the current soil sites enriched with kaolinite clay mineral. Fertilizer application must be carried out at the beginning of the rains, or towards the end of the rainy season (Pancel, 1999). Because fertilization at planting is first of all intended to support the development of the root system and not to replenish soil fertility.

Due to the very low percentage of available and total phosphorous at the three sites but relatively low soil P sorption capacity, estimated rock phosphate or any other granule fertilizer type and slower releasing with a high content of P such as Magamp is advisable for the establishment of South Sudan teak plantations. Such a choice relies on the fact that rock phosphate is less soluble than superphosphate, the one largely used in forestry plantations and, it shows lower leaching losses and longer duration response (Pancel 1999). Magamp (NPK=7:17:5) according to Kenneth and Shepherd (1986), is also a formulation of slow release of nutrient elements incorporated into tablets which are placed directly into the planting hole where nutrients will become available over a period of months. Care however must be taken that soil is kicked over fertilizer to prevent direct contact with roots.





<u>Figure 32.</u> Statistical comparative results of the soil available and total phosphorous (P) between the two lands uses: Outside "Out" and Inside "In" plantations at specific horizon (A:0-20 cm). The centered squares represent the sample means of P at land use and specific profile horizon. The vertical bars represent the 0.51 confidence interval of the mean variation.

As these authors comment, this chemical formulation of Magamp though more expensive than the older formulations, its transport and application can be cost saving as it is much more concentrated with nutrients.

Although less fertilizer applications are reported for hard woods such as teak, the management of *Eucalyptus* can be used as a model reference. Thus after the first application around the seedling at planting, the second application should take place at maximum seedling height of 5 cm but in any case, before the tree has reached the height of 1m as it is recommended for *Eucalyptus grandis* (Pancel, 1999).

In all, the available and total phosphorus, iron and Aluminum between the three sites sound contrary to the common view stated, as phosphorus in tropical soils is conditioned by its complexation with the formers; here however we observe that both phosphorus pools are dictated by the level of the organic soil matter. This might fiund its explanation in the dominance and type of iron signature of landscape and climatic condition in the area; in the present case it is goethite. Of all the three sites where the sorption indices are observed to be low, Yoboa presented the highest level of iron content and thus of P sorption index. In the absence of properly planned and monitored fertilizer trial, guidelines on phosphorus fertilizer application and/or recommendation at this stage can only be speculative and must be based on other similar experiments even of different species and not necessary teak. Such fertilizer applications will simply intend to support and boost the seedlings growth at planting and not to replenish the current very low phosphorus soil content; long term and sustainable build up or maintaining of phosphorous levels must be found in silviculture practice operations.

2.6. Available and Total Phosphorous, Iron and Aluminum as Land Uses Variables: Inside and Outside Teak Plantations

According to Attiwill and Adams (1993), if forest growth is limited by nutrients, then for much of the world's mid-temperate, warm-temperate and tropical forests growing on older, well weathered soils, the limiting element is most likely to be phosphorus. For example, forests of Eucalyptus spp. grow on soils which, by northern hemisphere standards, are mostly poor in both total and available phosphorus. Swaine (1996) also pointed out that phosphorus has been proposed as the nutrient most likely to be limiting in lowland tropical forest, giving the example of *Melastoma malabathricum* which was strongly P-limited in soil from rain forest in Singapore.

The investigation of available and total phosphorus in site classification has already shown a positive correlation with the soil organic carbon and thus organic matter content at the three sites. From such a result, it can be expected that a further investigation in respect of land uses grouping would show a higher predominance of both P pools under the fallow lands in contrast to soils underneath teak plantations. Such an expectation relies on the fact that fallow lands have more diversified and quantitative amounts of vegetation, high litter fall as organic matter and thus higher level of organic carbon can reasonably be excepted.

Once more and lastly, there is no statistical difference between the means of both phosphorous estimated pools between the two lands uses as shown in **Figure 32** and that is because the Kruskas Wallis p-values are all larger than the critical value of 0.05. However, even though both of the P pools are very low and particularly the available P which is almost nil, the relatively highest means values presented in **Table 13** and **Figure 33** occur as expected on the lands outside the plantations.

The reason for such an accumulation of phosphorus, the plant nutritive element recognized to stimulate early growth and roots development of seedlings, is related to the concentration of the organic matter fraction of most tropical soils to quote Alister, Smith and Sanchez (1997). Such a correlation of P and organic matter is also confirmed by the higher positive correlation of available P with soil organic carbon outside (R^2=0.2) plantations in contrast to that of the same pool of P inside plantations (R^2=0.06) presented in **Figure 34**.

Indeed in the range values of available P outside plantations, **Figure 34a** is around 0.3 mg/kg that of soils inside plantations, **Figure 34b** revolves, around 0.15mg/kg which is half that of the former. This high concentration of P under fallow lands as observed by Alister, Smith and Sanchez (1997), on which tenet the shifting cultivation is still being widely practiced in the tropical areas. Such a practice of shifting cultivation as these authors commented exploits the nutritional value of soil organic matter, invariably in areas where fertilizers are unavailable, and has also evolved as a means of utilizing soils with low nutrient retaining capacity. Long-term sustainability of soils in the humid tropics as they concluded always depends on the replacement of nutrients in the form of organic matter. This is normally achieved by allowing forest regrowth over a period of several years as forest clearing and cultivators move to an adjacent area.

Attiwill and Adams (1993) also observed that in natural, perennial ecosystems, much of the demand for phosphorus by plants is met by the cycling of phosphorus in organic residues and that, in Australia, the demand for phosphorus in stands of *Banksia* spp. appeared to be met almost entirely by mineralization of phosphorus in the litter layer.

No significant statistical differences is noted on the 0.05 p-value as all the Kruskas Wallis (P_{KW}) p-values (0.3. and 0.5) are larger than 0.05 However, the higher means variation of both P are observed on soils outside plantations. This makes them more fertile than the soils inside the plantation

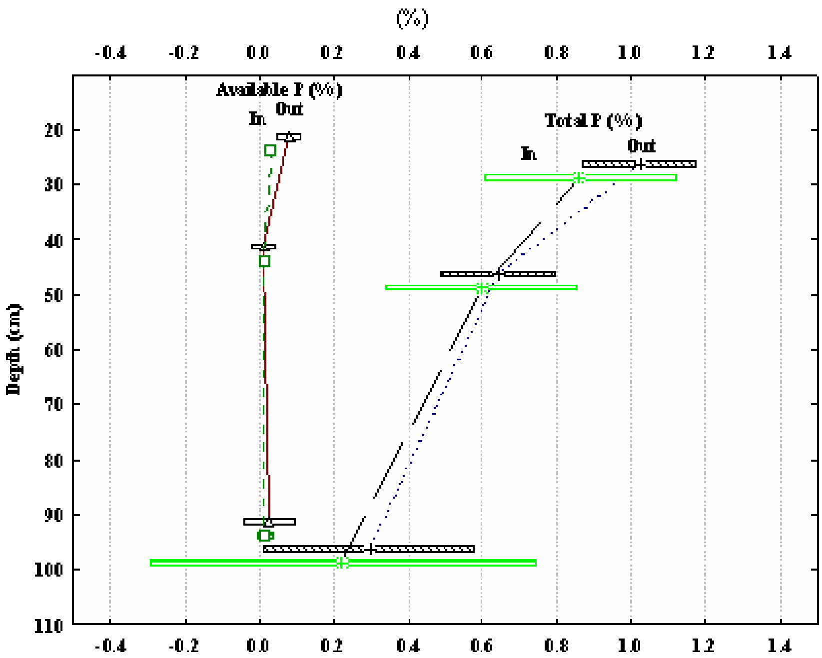


Figure 33. ***Soil available and total phosphorous (P) of the two land uses: Outside "Out" and Inside "In" plantations at different profile horizon: A:0-20 cm, B:20-40 cm and C:80-100 cm. The squares and crosses patterns represent sample means of phosphorous at land use at horizon. The horizontal rectangle bars represent the standard error of the mean variation.***

The highest concentrations of both available and total phosphorous are observed on the soils outside plantations with a significant decrease within profile depth. This indicates that the P input from the soil desorption expected, has lower contribution in comparison to that of soil organic carbon.

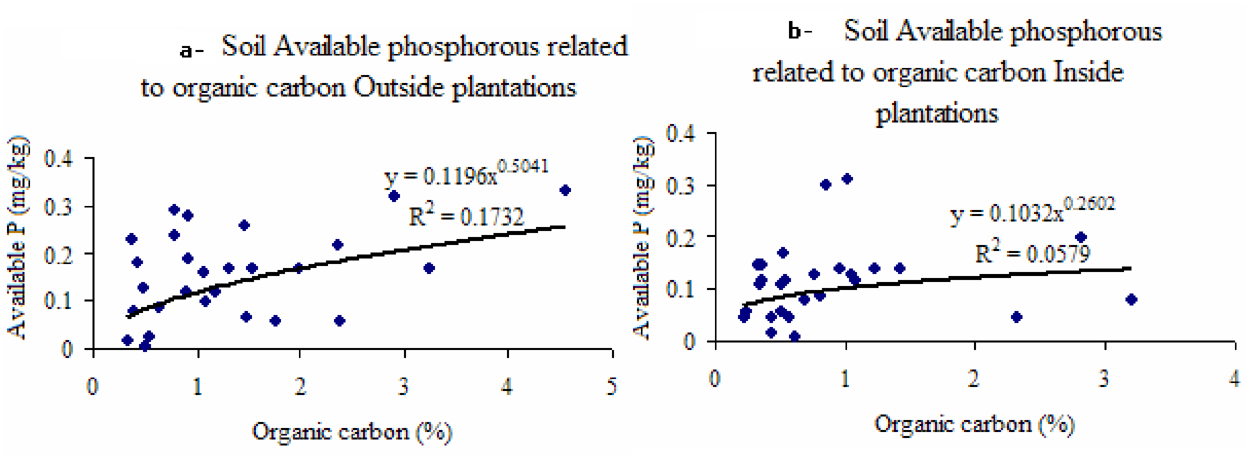


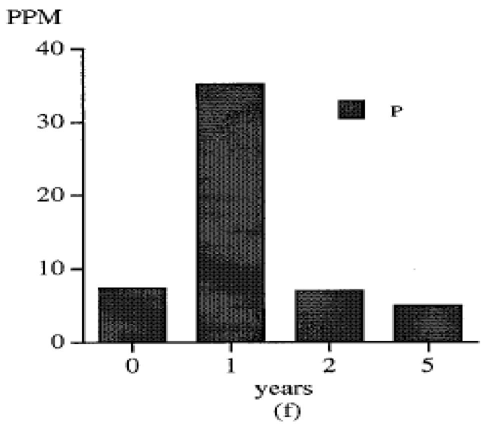
Figure 34. ***Available and total phosphorous (P) (mg/kg of soil) related to soil organic carbon content for all profile horizon: A: 0-20cm, B: 20-40cm and C: 80_100cm combined of both land uses: Outside and Inside plantations.***

There is a slight positive correlation (R^2=0.17) between available P and organic carbon on soil outside plantation compared to those inside (R^2=0.06) implying that available P of soil outside plantation is more depend on organic matter while inside forest P desorption may contribute as another source of P input. While the soil available phosphorous outside plantations ranges are around the value of 0.3 mg/kg these of soil inside plantations are half that value. This confirms a more effective nutrients recycling from organic matter outside plantations.

In the soil supply of phosphorous relying on the vegetation regrowth and mineralization, one needs to consider that not only the density of the vegetation cover will be a determinant for the P input but also the diversity of such a vegetative cover especially its foliage nutrient richness and particularly that in terms of phosphorous. As Attignon, Weibel and Lachat (2004) stated, leaves constitute the major part of the total litter fall, providing an important nutrient pool; the breakdown of leaf litter is a key component in nutrient cycling in tropical forests. This breakdown of litter as these authors argue depends on a number of abiotic and biotic factors comprising: microclimate, mainly temperature and humidity litter quality, in particular nitrogen, lignin and polyphenol concentrations and soil nutrient content ratios, the qualitative and quantitative compositions of decomposer communities including bacteria, fungi and invertebrates occurring mainly on topsoil. These authors also noticed that in contrast to natural forest types of vegetation in Benin, teak litter had the lowest quality and thus produced less organic carbon as they showed in **Table 12**. The relatively high level of phosphorous and particularly that of total P under fallow lands in contrast to forest plantation soils can also be related to the effect of repetitive litters burning on fallow lands. Indeed, ash is well recognized to play a similar role of fertilizer immediately after the burn since it then contains high a amount of cations and some anions such as phosphorous. This implies that recently burnt fallow lands which are certainly included among the whole set of lands under fallow will secure the higher availability of phosphorus on these soils.

On the other hand, high temperature as a result of burning is also expected to increase P fixation under fallow lands and thus the higher total P observed. As Alister, Smith and Sanchez (1997) observed**,** high temperatures as a result of burning can increase chemical and biological reaction rates in soil and this in turn may increase weathering and phosphorous fixation.

Despite the relatively higher range values of available and total phosphorous observed on soils outside the plantations, those values not only decrease with depth but moreover, they are in overall very low as percentages and also as part per million (PPM or $cmol_{(+)}$/kg) when compared with those for instance found by Alister, Smith and Sanchez (1997**)** in **Figure 35.** These authors attributed such low concentrations of P to the fast mineralization of organic matter under tropical areas and in the longevity of the fallow period. They found that the level of P increased tremendously during the first year after natural primary forests were cleared, burned and left to re-grow but most importantly, it then decreased significantly after that first year as can be seen in **Figure 35**. Since their experiment only considered a time period of 5 years on one hand and the fact that we do not know for sure the ages of the Nzara current lands on fallow which are expected to be more than 5 years for some plots on the other, one might speculate that current very low index concentration of P observed is simply a decreasing linear function of the fallow period for soils outside plantations. As pointed out by Cheryl, Swift, Woomer (1996), the large biomass and diverse vegetation of the tropical forest can store more than 50% of the nutrients of the system; forests on poor soils generally store a higher percentage aboveground than nutrient rich sites where the largest percentage of the nutrients are found in the soil. For these soils inside the plantations, the homogeneity of the litter fall in addition to the soil surface erosion and leaching prone to them is more likely to be the first insight for the explanation of their very low available and total P.



<u>Figure 35.</u> Changes in phosphorous (P) as parts per million (ppm= mg of P per kg of soil) status of topsoils with respect to primary forest clearance time (Adapted from Alister, Smith and Sanchez, 1997).

The P concentration of primary forest is in equilibrium as the forest sustains itself and this corresponds to the concentration of P at year zero. Soil P increases tremendously after the first year of clearance then decreases even below its level before its clearance.

The tremendous increase of P at year 1 is most probably due to the P concentration in the vegetative soil cover slashed and burned from the primary forest. The subsequent decrease can be speculatively explained by the low P concentration of the new regrowth vegetation forming the secondary forest. Each time the regrowth vegetative soil cover is cleared, the concentration of P in the next vegetative cover decreases below that of previous concentration level.

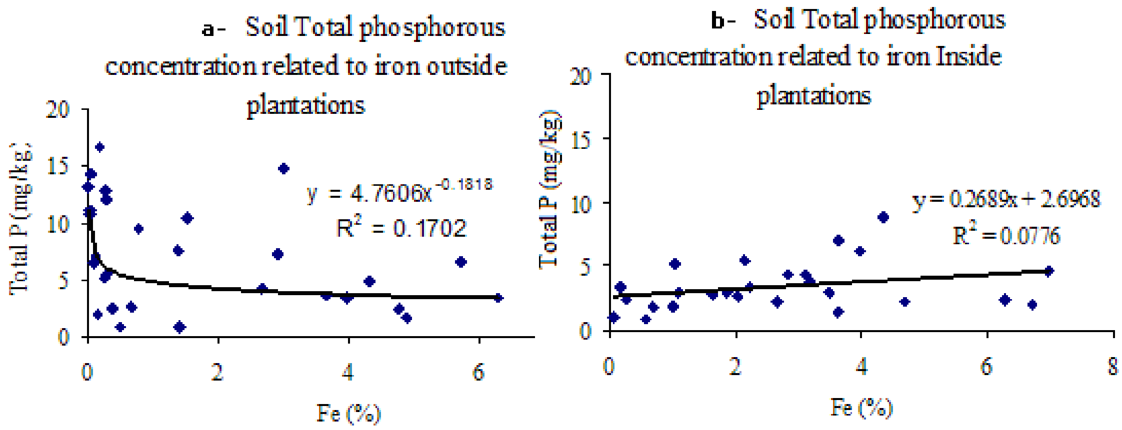
Species	%		C:N
	Carbon (C)	Nitrogen (N)	
Afzelia africana	46.1	1.8	26
Ceiba pentandra	44.7	1.3	34
Senna siamea	44.4	1.1	40
Tectona grandis	41.5	0.7	59

Table 12. Comparative concentration of carbon (C) and Nitrogen (N) between teak plantations litter matter and these of different other species from natural forest presumably of the same age in Benin (Adapted from Attignon, Weibel and Lachat, 2004).

Teak presents the lowest concentration of litter carbon but it has the highest C/N ratio of 59. With such a high ratio of C/N, the organic matter from teak litter is mainly raw material and unlikely to quickly break down (Hozelton and Murphy, 2007). Such a C/N of teak litter explains in part the low concentration of carbon organic content and S-value observed on soils under the teak plantation of the current study area of Nzara. The contribution of the iron ore (oxi-) hydroxides to the increase of total P between the two land uses appears to be predominant on soils outside plantation than on these inside plantation. This is shown by the observation of a higher positive correlation (R^2=0.17), **Figure 36a,** between total P and Fe% and the wider spread range of values up to 15m g/kg of total P in contrast to that of soils inside plantations (R^2=0.08), **Figure 36b** with narrower ranges around 10m g/kg of P.

This can be attributed to the occurrence of predominately amorphous iron stabilizing organic carbon hence the presence of more extractable P outside the plantations compared to the more crystalline irons where less sorbed P to be extractable is observed as suggested by Abekoe, and Tiessen (1998). According to them, small amounts of total and available phosphorous in most tropical soils are the result of their advanced weathering, variable P sorption and poor organic matter recycling. Under such an observation, one may comment that the soils inside the plantations which show the lowest availability and total of P are also subject to more advanced weathering conditions than the ones outside.

The support to such deduction can be found in the fact that by the more active impact of rainfall on the almost entirely bare soils underneath the plantations thus leading to accentuated water erosion.



<u>Figure 36.</u> Soil total phosphorous (Total P) as mg of P per kg (mg/kg) related to Citrate Bicarbonate-Dithionate (CBD) iron (Fe%) as a percentage of soils of the two land uses: Outside and Inside plantations all the profile horizons: A: 0-20 cm, B: 20-40 cm and C: 80_100 cm combined.

In both cases, there is a weak positive correlation between total P and Fe (R^2=0.17 and R^2=0.08), implying a low input of soil total P from Fe decomplexation under both land uses. The spread of individual observation on soil inside the plantation is however narrower and seems to increase with Fe %. The spread of individual observation on soil outside plantations on the other hand does not show a precise pattern even though it seems to decrease with F%. This implies that slightly more P sorption from Fe should be expected on soil inside plantations thus higher concentration level of Fe contributing to the level of total P.

Parameters	Outside Plantation				Inside Plantations			
	Top soil A(0-20cm) n=10	**Sub soil B (20-40cm) n=10**	**Deep soil C(80-100+) n=3**	**Total 0-100+cm**	**Top soil A(0-20cm) n=8**	**Sub soil B (20-40cm) n=8**	**Deep soil C (80-100+) n =2**	**Total 0-100+cm**
pH_{water}	6.4±0.2	5.5±0.2	6±0.5		5.8±0.2	5.4±0.2	5.4±0.6	
pH_{KCl}	5.5±0.2	4.3±0.2	4.7±0.4		4.8±0.3	4.2±0.2	4±0.4	
C%	1.95±0.3	0.95±0.1	0.55±0.1		1.56±0.3	0.77±0.2	0.45±0.1	
N%	0.13±0.02	0.07±0.01	0.05±0.01		0.09±0.02	0.06±0.01	0.04±0.01	
C/N	15.7±0.9	13±0.8	12±1.3		15.7±1	12±0.9	11±1.6	
Mg^{2+} (cmolc/Kg)	0.6±0.06	0.3±0.07	0.3±0.06		0.4±0.07	0.3±0.07	0.3±0.08	
Mg^{2+} (kg/ha)	***749±75***	**468±110**	**187±37**	***1,404***	***500±87***	***468±110***	***187±50***	***1,155***
Ca^{2+} (cmolc/Kg)	2.6±0.5	1±0.3	1.3±0.4		1.8±0.5	0.7±0.3	0.6±0.5	
Ca^{2+} (kg/ha)	***5,408±1,040***	***2,600±780***	***1,352±416***	***9,360***	***3,744±1,040***	***1,680±780***	***624±520***	***6,048***
K^{+} (cmolc/Kg)	0.04±0.007	0.02±0.007	0.01±0.002		0.02±0.007	0.01±0.008	0.01±0.003	
K^{+} (kg/ha)	***81.12±14***	***51±16***	***9.4±1.9***	***142***	***41±14***	***24±15***	***9.4±1.8***	***74***
Tot K^{+} (cmolc/Kg)	0.08±0.02	0.08±0.02	0.05±0.02		0.04±0.02	0.04±0.02	0.03±0.03	
Tot K^{+} (kg/ha)	***162.24±41***	***204±51***	***47±20.28***	***413***	***82±41***	***102±51***	***30±30***	***214***
Na^{+} (cmolc/Kg)	0.03±0.002	0.03±0.001	0.03±0.001		0.03±0.002	0.03±0.001	0.03±0.002	
CEC (cmolc/Kg)	3.3±0.5	1.4±0.3	1.6±0.4		2.2±0.6	1±0.4	1±0.5	
Avail P%	0.08±0.04	0.01±0.004	0.02±0.007		0.03±0.04	0.01±0.004	0.01±0.007	
Avail P (kg/ha)	***4.2***±2	***0.7±0.3***	***0.5±0.2***	***5.4***	***1.6***±2	***0.7±0.3***	***0.3±0.2***	***2.6***
Tot P %	1.02±0.2	0.6±0.1	0.3±0.2		0.9±0.3	0.6±0.2	0.2±0.2	
Tot P (kg/ha)	***53±10***	***39±7***	***8±5***	***100***	***47±16***	***39±3***	***5±5***	***91***
TotP/Avail P	28±26	63±17	17±12		74±29	66±18	20±12	
Al^{3+}%	0.45±0.1	0.5±0.2	0.6±0.14		0.35±0.1	0.6±0.2	0.4±0.17	
Fe^{3+}%	1.4±0.7	1.4±0.6	1.6±0.6		3.7±0.7	3.8±0.7	1.7±0.7	
Fe^{3+}/Al^{3+}	5±1.3	4±0.8	3±0.9		4±1.2	6±0.9	5.3±1	

♣Table 13. ***Summary results of sample means and their standard errors of all soil chemical properties under both land uses.Outside and Inside plantations at all the profile horizon: Topsoil-A:0-20cm, Subsoil-B:20-40cm and Deepsoil-C:80-100cm.***

♣ Kg/ha was obtained by using the ppm values, using the horizon depth (cm) on 1 hectare and the horizon bulk density derived from texture in Appendix C-4.

Tectona grandis	Nigeria	West Africa Countries	
	Annual "requirement" Kg/ha/yr	Soil nutrient reserves	
		"Available" store Kg/ha/root-depth	Total store Kg/ha/root-depth
N	160-328		3682±1270 N_{tot}
P	32-76	580±350 P^{av}	
K	260-556	392±267 K_{ex}	12200±11200 K_{tot}
Ca	145-357	5688±4554 Ca_{ex}	14000±15000 Ca_{tot}
Mg	47-62	994±740 Mg_{ex}	5800±5400 Mg_{tot}

***Table 14.* Total aboveground nutrient "requirement" (kg/ha/yr) of Tectona grandis (class I best teak performance stand, Nigeria) at the age of 9-15 years in comparison with the soil nutrient reserves in West Africa Teak plantations (Pancel, 1993).**

Soils outside plantations show higher concentration of major plant nutrients in top soils and this is decreasing with the depth. The soils under fallows are more fertile than their counterparts under the plantations.

According to **Table 14,** phosphorous (P) is the element the least required (32-76 kg/ha/yr) and it is also among the least available (580±350 kg/ha/yr). It is followed by magnesium (Mg) in terms of demand (47-6 kg/ha/yr 2). Potassium (K) on the contrary is the most required (260-556 kg/ha/yr) but the least available (392±267 kg/ha/yr) in contrast to calcium (Ca) also highly required but the most available. This implies that teak stand management under tropical forest plantation such as Nzara must be operated in a manner that would be supplementing and/or sustaining the soil levels of P and K in particular.

In summary, the Ferralsols present under tropical soils are generally poor[1]. The soils of Nzara district of South Sudan do not constitute an exception. As Hance (1955) said, the soils of Nzara are laterized, are of low fertility and susceptible to erosion. However, even though there is a lack of sufficient information about these soils' land uses prior to the establishment of teak plantations, one can deduct from visual observations of the soils under both land uses in addition to the current results that the present management of these established teak plantations are aggravating the degradation and fertility of the soils under these plantations.

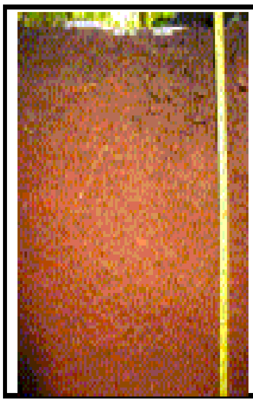
[1] See for instance USDA (2004), Sanchez (1976), FOA/UNESCO (1974).

2.7. Dominant Soils Groups and their Characterization (see also Appendix A for the additional Soil Forms and Families)

The physical and chemical properties of soils of the three sites discussed so far can be grouped into six major soil types when referring to the South Africa Soil Classification or three when referring to the United State and the French Soil Classification these are: Nomanci 1100 (Oxisol or Soils Ferralitique Fortement Desatures) – Sweetwater (Alfisol or Soils Ferrugineux Tropicaux Lessives):1120/1220 – Longland 1000 – Westleigh: 1000 - Inanda (Oxisol):1200 – Dresden (Oxisol):2000 – and Hutton: 3200 were described and analyzed (**Appendix A**). Of these soil types, the occurrence of five (Nomanci: 1100 -Sweetwater: 1120/1220 – Inanda: 1200 and Dresden: 2000) predominant on the site and presented below; the other are found in **Appendix A1**. These soils can be separated into two major groups: the watershed mosaic and the alluvial complex. The watershed groups are mainly characterized by their shallowness due to the presence of an iron concreted layer near the surface; the alluvial on the other hand are the deeper ones as they are the result of recent fluvial water deposit. Being unsuitable for aforestation, the alluvial complex is largely ignored here. Following are the main soil types of the watershed mosaic and a summary of their characteristics and suggested suitability ratings for aforestation.

A large proportion of soils were found to have humic top soils. The Soil Classification Working Group (1991) uses the cut off values of 1.8% for the soil organic carbon content and 4 cmol (+)/kg for the S-value to define a top soil diagnostic horizon as humic A horizon. The term luvic which refers to an increase of clay percentage in the sub soil compared to its overlapping is also commonly used to distinguish between diagnostic B horizons at the form level.

Figure 37a.



Depth (cm)	pH		Texture	S-value (cmol+/kg)	C%	C/N	Avail P (mg/kg)
	water	KCl					
20	6.12	4.51	SaClLm	3	1.17	13	0.1
60	5.59	4.14	SaClLm	2	0.6	12	0.1
100	5.54	4.35	SaClLm	1.2	0.4	11	0.1

Brief description: Station 4 Inside plantation Inanda 1200 (1 = Best on a suitability scale of 1 to 4)
Humic A: dark color, very low S-value
Red apedal B; Clay increase (luvic) and thin A horizon of 20cm (1200), very deep

Figure 37b.

Depth (cm)	pH		Texture	S-value ($cmol_+$/kg)	C%	C/N	Avail P (mg/kg)
	water	KCl					
15	6.53	5.98	SaClLm	9.85	2.9	16	0.3
60	5.98	4.95	SaCl	5.97	1.76	16	0.1
100	5.96	4.65	LmSa	2.06	0.37	15	0.2

<u>Brief description:</u> Station 30 Outside plantation, Sweetwater 1120 (2 on a suitability scale of 4)
Humic thin A (15cm) horizon
Neocutanic non-red luvic B horizon, very deep soil, low to neutral pH.

Figure 37c.

Depth (cm)	pH		H^+ mg/kg	Al^{3+} mg/kg	Texture	S-value ($cmol_+$/kg)	C%	C/N	Avail P (mg/kg)
	water	KCl							
35	5.61	4.53			SaClLm	1.16	0.8	15	0.13
55	5.25	3.94	0.41	0.46	SaClLm	3.9	0.6	14	0.12
			0.87						

<u>Brief description</u> Station 7 Inside plantation Dresden 2000 (3 on a suitability scale of 4)
Orthic bleached A horizon with very low organic carbon
Hard plinthite B, shallow soils, low pH with Aluminum saturation

Figure 37d.

Depth (cm)	pH		H+ mg/kg	Al^3+ mg/kg	Texture	S-value ($cmol_+$/kg)	C%	C/N	Avail. P (mg/kg)
	Water	KCl							
10	5.38	3.98	0.27	0.32	SaCl	11	1.73	10	0.7
			0.59						
38	4.98	3.99	0.45	0.49	SaCl	8	1.52	13	0.2
			0.94						

<u>Brief description:</u> Station 1 Inside plantation, Nomanci 1100 (4 = worse on a suitability scale of 4)
Humic thin A horizon
Lithocutanic B, very shallow soil, low pH with Aluminum saturation

3. Spatial Distribution of the Dominant Soil Forms (see also Appendix A for additional Soil Families and Forms)

The distribution pattern of all the soil forms appears in **Figure 38** below. From that map, it can be seen that the worse soil forms Dresden were located at the Nangondi and Yoboa sites and are associated with laterite outcrops. Nomanci the second worse and the all the other forms on the other hand are widely spread all over the three sites. A detailed geomorphological map of the area which is currently lacking would have certainly localized the Dresden and Nomanci forms on the watershed and the other near the river meanders where they would be of fluvial deposition. On the basis of these considerations, the Mabarizinga site area the is currently advisable for more Teak plantations establishment or extension.

This recommendation was already made by Kamal et al (1989) where they suggested that Teak will grow on soils overlying ironstones provided the area is prone to heavy rainfall such as Yambio among others and that outside the wetter parts of Equatoria ar El Ghazal Provinces Teak can only be grown on very limited sites. The suitability of this area for Teak and the can also be explained by the presence of the river meanders which will help in keeping the subsoil in a moist water regime. In doing so the laterite layer will remain in a more reduce potential and therefore soft enough for tree roots to penetrate through. Any intensive mechanical management able to reduce the thickness of the humic A horizon should then be avoided as far as possible because it would expose the laterite layer to more oxidative potential.

The soil forms were described and classified according to the South Africa soil classification 1991. The red color pattern indicates the least suitable soil forms while the green indicate the most suitable soil forms (**Figure 38**). The best soil forms in terms of their physical and chemical properties are dominantly found towards the Southern part of the study area: around the Yoboa and Mabarizinga teak plantations. It will thus be reasonable to extend the establishment of new teak plantations around these two plantations and preferably towards their West and Northern parts. The present distribution is however not systematic and soil survey should be done to confirm the current observation patterns.

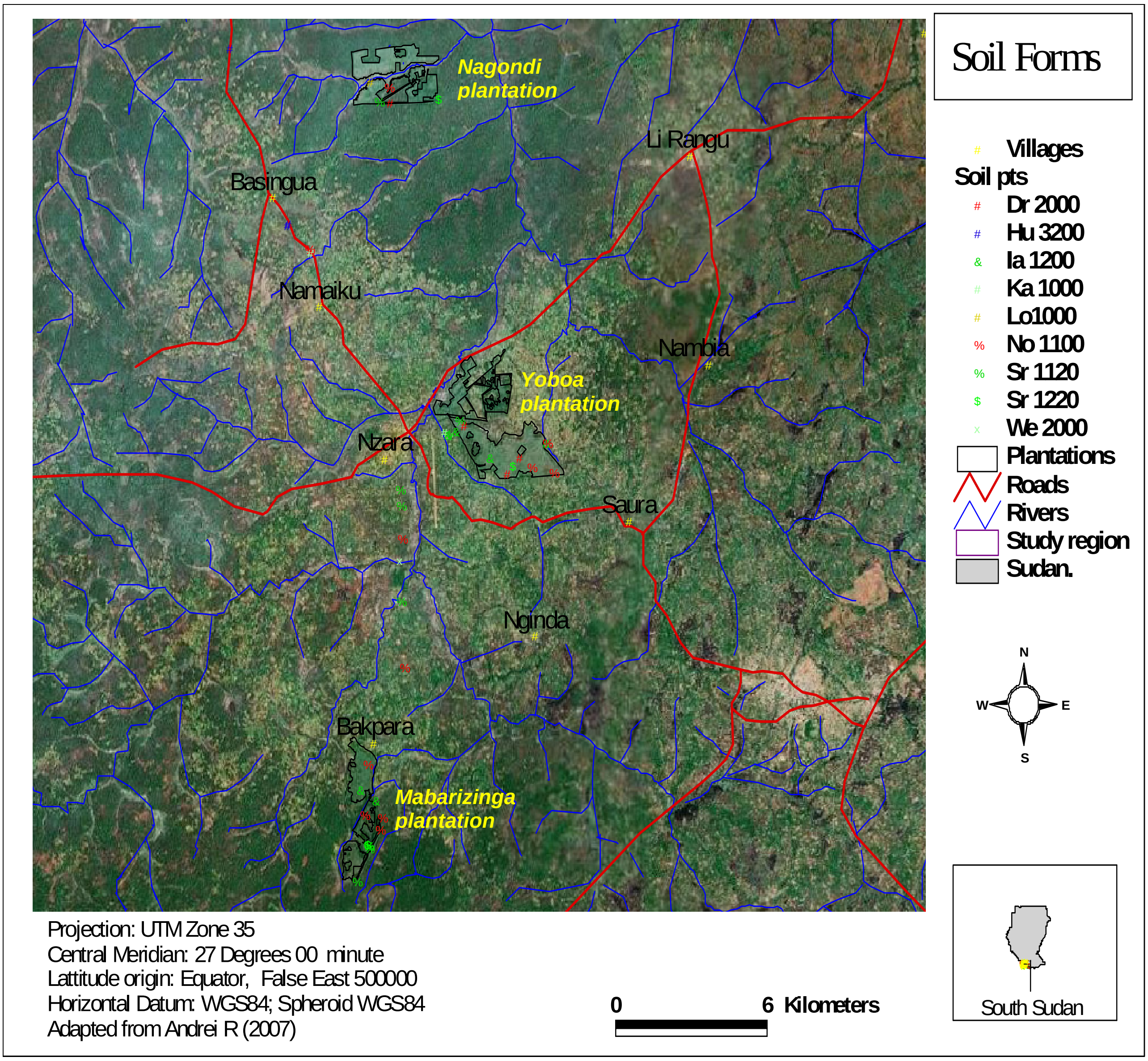


Figure 38. ***Spatial distribution of sampling locations and major soil forms and families of the three sites: Nagondi, Yoboa and Mabarizinga around the three existing teak plantations*.**

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IV. GENERAL CONCLUSION

One of the basic strategies for reforestation and forest management, stipulated in the International Tropical Timber Organization (ITTO) Action Plan is to establish tree plantations on degraded forest lands to provide sustainable timber production and to reduce the dependency on natural forests (ITTO, 1990).

The extension and/or new establishment of plantations of a valuable hardwood species such as teak (*Tectona grandis*) in the Nzara district of the Equatoria province in South Sudan answers that need. The distinction and classification of such lands to be allocated to forest plantations or food crops production can be obtained on a scientific level by soil analysis of physical and chemical properties related to previous land use together with geographic information.

From the investigations undertaken on the soils of Nzara area, combined with their previous and ongoing uses as slash and burn fields altogether with geographic data of the area and in comparison to other tropical countries where teak is being grown, it emerges that in general positive considerable returns can be expected. Climatic data of the area fall within the limits of areas where teak grows naturally and that of the world dominant producers: mean annual rainfall 1350-1600 mm with a distribution over 6-8 months compared to those of Myanmar 1250-3750 mm and Indonesia 1511-2108 mm, both with at least 3 months of dry season; mean annual temperature of 28-35^{0}C compared to 15-41^{0}C and 30-32^{0}C of Myanmar and Indonesia respectively.

No stastically meaningful differences in soil characteristics were found between the three plantation sites: Yoboa, Mabarizinga and Nagondineither or between the two land uses: inside existing plantations or outside them of (considered to be fallow lands of different ages). Mabarizinga was followed by Yoboa if site quality should be prioritized.

Both sites had more favorable soil texture compared to Nangondi. Both sites are also characterized by better soils chemical properties: pH_{water} values range from 6.4±0.56 and 6.04±0.7 in top soils; 5.91±0.5 and 5.46±0.61 in subsoils at Yoboa and Mabarizinga respectively. These values also fall into the interval of 6.5-7.5 of Myanmar and 5.2 and 5.5-8 of North West Costa Rica and Benin respectively. The highest soil organic matter content (1.8±0.34% and 1.92±0.43 in top soil and 0.89±0.16% and 1.13±0.19% subsoil) which determines soil nutrient availability were observed at the Mabarizinga site. At that site followed by Yoboa, were also recorded the highest Cation Exchange Capacity (S value: 3.18±0.6 and 2.7±0.76 cmolc/Kg for topsoils); the higher available (0.09±0.04% and 0.03±0.04% on topsoils) and total phosphorous levels (1.19±0.26% and 0.9±0.3% also on topsoils). All these levels of macro-elements while being very low as percentages were not too far from those of other tropical Ferralsols in the areas of, for instance Nigeria and other West African Countries where teak is grown. These suggestions of higher land suitability for teak further south of Nazara are a confirmation of what Kamal et al (1989) already recommended. Although the formulations of their recommendations were largely based on the higher rainfall rate registered in the area.

The soils outside the existing teak plantations on the other hand appear less degraded and more fertile. Beside the fact that their texture is mainly Sandy Clay Loam with a higher percentage of clay content, these soils outside teak plantations had higher values of pH_{water} (6.4±0.2 compared to 5.8±0.2 on topsoils), organic carbon (1.95±0.3% and 0.95±0.1% respectively against 1.56±0.3% and 0.77±0.2% in topsoils and subsoils respectively); S-value (3.3±0.5cmolc/Kg and 1.4±0.3cmolc/Kg compared to 2.2±0.6 cmolc/Kg and 1±0.4 cmolc/Kg also on topsoil and subsoils respectively); the available and total phosphorous of 0.08±0.04% and 0.01±0.004% against 0.03±0.04% and 0.01±0.004% for topsoils and subsoil respectively for the former; 1.02±0.2% and 0.6±0.1% compared to 0.9±0.3% and 0.6±0.2% on topsoils and subsoils respectively for the latter. The above values, although slightly higher than underneath teak plantations are not much different from other similar tropical soils subject to the practice of slash and burn regulated by the regeneration of vegetations as the land is abandoned or left under fallow for long periods of time.

However, such a slightly higher fertility of soils outside teak plantations demands considerable attention and care in the forester’s finial decision to avoid any probable conflicts that might arise with local communities who might see their lands being confiscated by foresters when the fallow period reaches its intending end.

V. MANAGEMENT RECOMMENDATIONS

"The question to be asked should not be, for example, 'is this a good banana soil?' An approach which places too much emphasis on the inherent, stored fertility which will rapidly be used up during the first cropping cycle. Rather, the question should be 'can this soil be made to grow bananas, and if so, at what cost and return?'' (Young, 1976).

Since the nutritional level of ferralsols in tropical areas is dependant on organic matter and the highest level of plant nutrients and best physical properties were seen to be on fallow lands in contrast to soils underneath teak plantations, the following recommendations aim at building and/or maintaining the soil organic matter through a number of silviculture practices.

Silviculture can be defined a set of management operations that aim at boosting the forest plantation productivity by reducing to a certain degree the rotation length of the stand while the quality of the product, the social needs and expectations of local communities around the stand and the preservation of the environment are still being met. These operations include among others: selection of the best planting materials; fertilizer application; thinning, pruning, and crop mixture also known as Agroforestry.

1. Planting Material Selection

According to Evans and Turnbull (2004), it has taken foresters a long time – much too long – to recognize that intensive forest management activities, such as site preparation or fertilization, will never yield maximum return unless the genetically best trees are also used. Palanisamy and Subramanian (2000) also noticed with desolation that in respect of teak (*Tectona grandis* L.), one of the important high quality timber yielding species in the world, most of the planting stock is still produced from seeds of unselected sources. Low quality seed and poor germination rates affect the availability of planting stock. That author further remarks clonal plantations of genetically improved *Eucalyptus* raised through cuttings enhanced the productivity 4 to 7 fold compared to plantations of unimproved seed origins.

According to Kamal, Badi El Houri, Aziz and Bayoumi (1989), not only the origin source of the South Sudan planted teak is unknown but the current seedlings in the nursery are still being produced from the seeds of standing trees in the plantations. Encouragement towards seedling production from cuttings of selected trees in absence of possibilities to buy high quality from large teak producers such as Indonesia and India, should be a considerable priority for the establishment of future plantations. However, as to use Evans and Turnbull's (2004) words, in recent years, foresters have learned from bitter experience that no matter how excellent trees may be genetically, maximum production cannot be achieved unless good forest management practices are used along with the improved plants. This is to say that not much should be expected out of an appropriate selection of the teak seedlings if physical land management is not undertaken to maintain the viability of the soils on which they are planted.

2. Fertilizer Application Estimation and Recommendation

Most experiments designed for mineral fertilizer recommendation have been done uniquely for application in the field of food crop production. Tree seedlings considered as crops can also take advantage of these recommendations particularly at planting and up to a certain height. The heart of the problem in mineral fertilizer application in the tropics even for food crops is their high price from their produced point to the farmer's door, their transportation, storage and knowledge on their proper and effective application. Even when most of these parameters are met, it is still important that mineral fertilizer application at the time of planting is only intended to help seedlings with rooting and early development and not to sustain the stand all along the rotation length. As Kenneth and Shepherd (1986) said, it is undoubtedly true that during the initial stages of development of a plantation up to canopy closure, the demands for nutrients from the site will be very high and responses to a wide range of fertilizer nutrients are to be expected.

Pancel (1993) also remarked that in the early stages of stand development prior to canopy closure, the annual rate of nutrient accumulation increases rapidly and tree growth is very dependent on current nutrient uptake. Mineral deficiencies are frequently observed and responses to the application of fertilizers are common during this period. Once the canopy has closed, the reduction in rate of nutrient accumulation is associated with attaining maximum foliage biomass, high internal retranslocation of mobile nutrients (N: nitrate form, Mg, K…less mobile elements: Ca, Si, Mn, Fe) as well as increasing amounts of nutrients in litter fall and by capture from the atmosphere. This will decrease the nutrient contribution by soil reserves to the amount incorporated in the wood or less. Therefore, fertilizer response will be unlikely during this second stage, unless thinning will not return the stand to its first stage prior to canopy closure.

In these instances, beyond the level of canopy closure, unless mineral fertilizer application follows thinning and/or pruning operations to meet the stressed remaining trees, mineral fertilizer might be merely washed away or leached out resulting in water bodies or pasture contamination.

3. Thinning

According to Kenneth and Shepherd (1986), the deep and fertile alluvial soils are rarely available for tree crop production as these are preferred sites for agricultural cropping and therefore forests are more likely to be established on less fertile soils, on residual soils which frequently are deficient in one or other of the important nutrient elements. In such a context, forest plantations established for more than 50 years in the case of hard wood such as teak, thinning should be viewed as by far the most beneficial operation of forest plantation stands. This is because it reduces the competitive effect among trees through a plan of operation that removes a number of selected trees, allowing the remainder ones to increase particularly in diameter (Evans and Turnbull, 2004; Kenneth and Shepherd, 1986; Pancel, 1993).

As Pérez (2005) said, an efficient way to increase teak plantation productivity is to optimize stand density and rotation age. Pérez (2005) for instance concluded after evaluating a spacing trial in Nigeria that *T. grandis* should be planted at densities between 1189 and 1680 trees ha^{-1}, as individual tree growth declines at higher densities and stand growth potential is not reached at lower densities.

Zanin (2005) also reported that for optimum development of a stand, thinning is essential because it is a silvicultural treatment that reduces size differences and increase stand uniformity. In this case as she concluded, fertilization is not needed to increase the diameter growth of trees, instead timely thinning is recommended and it should start at the onset of competition, the indication of which include the touching of crowns and mortality of lower branches. Evans and Turnbull (2004) for example reported that in Nilambur, Kerela state, India teak plantations are thinned six times during a 50-55 year rotation, which reduces the number of tree from $2500ha^{-1}$ to 100-150; in Costa Rica teak plantations were established at $1111ha^{-1}$, which by rotation age of just 25 years were reduced to $220ha^{-1}$. Obviously the implementation of thinning operations depend largely on goals pursued for the stand by the forester and/or government agency, the cost of such operations in comparison to their returns and the availability of a market.

As thinning will improve the quality of the stand’s final product, it will also at the same time provide substantial benefits, financial and social returns all along the stand’s rotational length. At the forester agency level, this is achieved by the continuous trade of removed trees, proving then to be an intermediate financial return from the plantation or gain of services from the local communities to whom the logs can be traded to. At the local communities’ level, thinning will ultimately provide job opportunities as man power for the implementation of the operations. Moreover, local communities will also be the first to profit from the thinned logs for their house needs in the form of poles or fire wood. In the particular case of South Sudan teak plantations, according to Kamal et al (1989), the only thinning operations undertaken on these stands since their establishment 60 years ago are those undertaken by thieves. The authors however admit that the current low teak productivity on the stands observed could considerably be boosted and reach those of India if proper thinning was undertaken. It is therefore of primary concern for thinning to gain considerable attention in the management planning of future teak plantations for the area.

4. Pruning

Pruning as the artificial removal of certain branches on the tree stem tends to maintain such a soil organic matter level while at the same time improving stem and wood quality. According to Evans and Turnbull (2004), while branches remain on the stem of a tree, the wood laid down contains knots; pruning is thus the removal of branches from the stem so that knot-free timber is produced. However as these author comment, in the case of some hard wood species such as teak, pruning is not always intend to produce knot-free wood as adventitious branches or epicormic shoots are easily formed; Rather pruning is required to improve stem form. Whatever its aim, the most important point here is the fact that pruning produces considerable amounts of litter fall which will be recycled and taken up again by the stand trees. As observed by Nambiar and Brown (1997), in plantation forest ecosystems, a large proportion of the net primary production is shed annually as litter; the greatest contribution to soil humus layer is from the litter, mainly from the detritus falling from the trees onto the soil surface.

The amount of nutrients delivered by litter fall to the forest floor is therefore of great importance for sustainable wood production and can provide an index of plantation forest productivity**.**

The practice of pruning can also be seen as a mere way of the environmental preservation and particularly that of soils against water impact leading to water erosion. Indeed, under tropical high rainfall areas such as South Sudan, the covering of soil underneath the tree stands during particularly the rainy season will be a highly effective measure to preserve the already poor top soils from being physically washed away by water. Practically, according to Zanin (2005), three prunings are recommended for teak; the first pruning should take place between the ages of two and three when the majority of trees reach five meters in height and have a diameter of six centimeters. On average, half of the total height of the tree should be pruned. Anything more can damage the total photosynthetic capacity and, consequently, growth will slow. The second pruning should take place in the fifth year or when the trees reach ten meters in height. The last pruning should remove 60% of the total height when a tree reaches twelve meters or seven years.

As a forester agency benefit, pruning may serve as a mean of weed suppression thus acting as a method of weed control. Once again, local communities surrounding the stand will provide the first man power in the undertaking of the operation; it can constitute a source of jobs for local communities and add a recreational value to the area. Pruning and thinning are key silvicultural activities, and together with the rotation length, are decisive factors for achieving different levels of quality and yield of round wood products (Pérez, 2005). However, as with thinning, the operational cost of pruning in comparison to its return must be fully justified before the operation is implemented. This implies the availability of a market willing to appreciate the high quality of the wood as the final product.

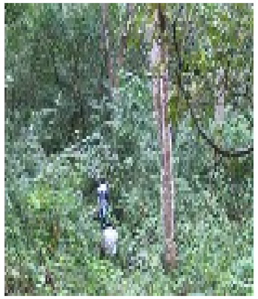
5. Agroforestry

A sustainable alternative to mineral fertilizer application is the implementation of a mosaic vegetation mixture between crop, teak and vegetation for other purposes. The vegetation for other than the cash crop aims at keeping a viable biotic and abiotic micro-environment necessary for the life and activities of litter fall mineralizers underneath the tree canopy. This will not only physically protect the soils underneath the teak canopy against water erosion and accidental fire but it will also serve as a relatively continuous pool of soil nutrient reserve.

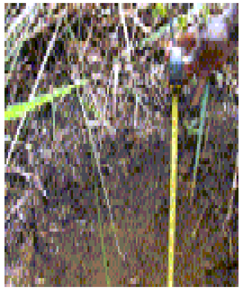
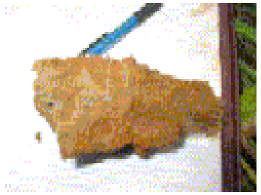
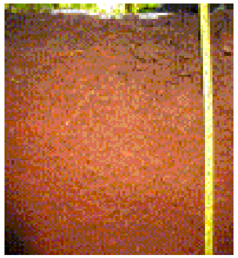
Mononculture plantations, if not properly managed can have adverse impacts on the environment. Soil erosion under teak plantations are much observed and largely criticized. Moreover, teak itself is a broad-leaf species and its larger leaves create bigger rain drops, causing greater impact on the ground and leading to disintegration of soil aggregates. This process could increase soil erosion if there is lack of sufficient ground cover (Zanin, 2005). Raymond (1996) also recognizes that soil erosion in teak plantations, both in Burma and India, has been confined to areas where undergrowth has been cleared and where burning has been excessive. Management which maintains a protective understorey of favorable species can probably avoid both soil erosion and site deterioration under pure stands of planted teak. Legume plants are widely advised to play such a role of understorey since most of the species have a natural ability to fix nitrogen one the major plant elements from the atmosphere. Kumar, Kumar and Fisher (1998) for instance found that intercropping *Leucaena* promoted height and diameter growth of teak. These authors found that teak growth increased with increasing relative proportion of *Leucaena* in the mixture. However, in establishing such a management of mixture, care should be taken that the legume does not strive to be the cash crop by severely competing with it. The ratio proportion of the mixture thus could be detrimental to the management success. In their experiment, Kumar, Kumar and Fisher (1998) observed that teak saplings in 1:2 teak-*Leucaena* mixture showed significantly higher radial growth than other combinations and, that average height and diameter decreased in the order: 1:2 teak-*Leucaena* > 1:1 teak-*Leucaena* > 2:1 teak-*Leucaena* > 100% teak. The need of planting and/or maintaining forest plantations understorey is crucial especially for forests established on hill slopes prone to increase the intensity of water erosion. As suggested by Zanin (2005), erosion is a problem within teak plantations; extensive erosion occurs when teak is planted on a hillside. It is therefore recommended not to plant on hillsides with more than a 20% degree of elevation to prevent heavy erosion; spacing on a hillside should be set wider apart to allow an understorey to grow.

VI. **APPENDIX A**: Sites and soils profiles description at the observation points (According to the South African Soil Classification Working Group, 1991) in the vicinity of Equatoria Teak plantations (Nzara, South Sudan). *The description of the location and the geographic coordinates of the profiles and their depths were adapted from the Andrei Rozanov (2007) report who, as already mentioned in page 21 did the field work that is the sampling. However, the Chemical and Physical soil characteristics were analyzed and estimated by the candidate who assigned the profiles form and family.*

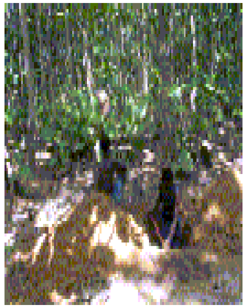
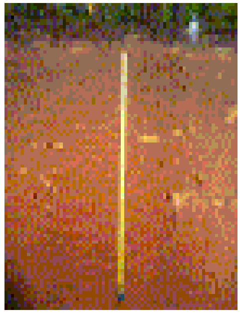
A-1: Profile Scenery, Description, Family and Form

Station	Altitude	Scenery	Profile	Detail_1	South Africa Soil FAMILY
30	**655**				Humic A (Thin) (C%>1.8, BS~4, weel drained) Neocutanic B (Luvic) **Soil Form and Family** **Sweetwater (Sr) 1120.**
37	**603**				Orthic A E (grey when dry) Soft plinthite B **Soil Form and Family** **Longland 1000 (E grey when dry)**

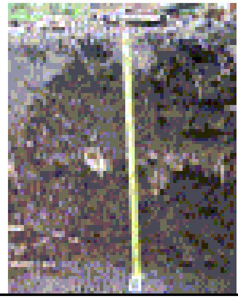
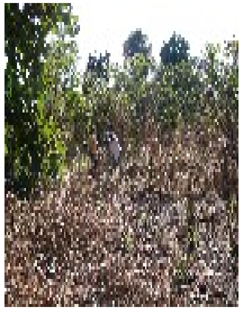
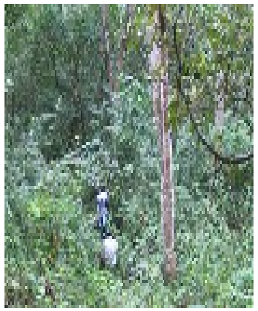
A-2: Profile Scenery, Description, Family and Form

Station	Altitude	Scenery	Profile	Detail_1	South Africa Soil FAMILY
4	**605**				Humic A (dark color,BS>4, C%>1.8) Red apedal **<u>Soil Form and Family</u>** **Inanda (Ia) 2200 (Clay increase-thick A 30cm)**
3	**600**				Orthic A with organic matter G Horizon (Non calcareous) **<u>Soil Form and Family</u>** **Katspruit (Ka) 1000**
4	**604**				Humic A Red Apedal B (Luvic) **<u>Soil Form and Family</u>** **Inanda (Ia) 1200**

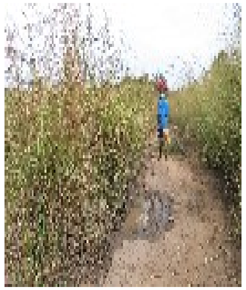
A-3: Profile Scenery, Description, Family and Form

Station	Altitude	Scenery	Profile	Detail_1	South Africa Soil FAMILY
5	**612**				Humic A (Thin) (C%>1.8, BS~4, well drained) Neocutanic B (Luvic) **<u>Soil Form and Family</u>** **Sweetwater (Sr) 1120.**
6	**636**				Humic A Red Apedal B (Luvic) **<u>Soil Form and Family</u>** **Inanda (Ia) 1200.**

A-4: Profile Scenery, Description, Family and Form

Station	Altitude	Scenery	Profile	Detail_1	South Africa Soil FAMILY
9	**630**				Orthic A bleached Hard plinthic B **<u>Soil Form and Family</u>** **Dresden (Dr) 2000**
23	**625**				Humic A (Thin) (C%>1.8, Bs~4, well drained) Neocutanic B (Luvic) **<u>Soil Form and Family</u>** **Sweetwater (Sr) 1120**
30	**655**				Humic A (Thin) (C%>1.8, BS~4, weel drained) Neocutanic B (Luvic) **<u>Soil Form and Family</u>** **Sweetwater (Sr) 1120.**

A-5: Profile Scenery, Description, Family and Form

Station	Altitude	Scenery	Profile	Detail_1	South Africa Soil FAMILY
26	**616**				Orthic A Soft plinthic B (non luvic) **Soil Form and Family** **Westleigh (We) 1000**
27	**618**				Orthic A Neocutanic B (Luvic) **Soil Form and Family** **Oakleaf (Oa) 1220**
29	**668**				Humic A (Thin) (C%>1.8, B~4, well drained) Neocutanic B (Luvic) **Soil Form and Family** **Sweetwater (Sr) 1120.**

A-6: Classification of correlation model profiles

SA[1]_form	SA_family	USDA[2]	FAO/UNESCO[3]	WRB[4]	US[5].	French System (ORSTOM)[6]	Texture
Dr	2000	Petroferric Haplustox	Petroplinthic Ferralsol	Petric Plinthosol	Oxisols	Soils Ferralitique Fortement Desatures Typiques ou Humifies	SaClLm
No	1100	Petroferric Sombriustox	Petroplinthic Ferralsol	Petric Humic Plinthosol	Oxisols	Soils Ferralitique Fortement Desatures Typiques ou Humifies	SaClLm
Ia	1200	Typic Sombriustox	Humic Ferralsol	Rhodic Humic Ferralsol	Oxisols	Soils Ferralitique Fortement Desatures Typiques ou Humifies	SaClLm
Oa	1220	Petroferric Haplustults	Ochric Luvisol	Plinthic Chromic Lixisol	Alfisols	Soils Ferrugineux Tropicaux Lessives	SaClLm
Sr	1120/1220	Typic Plinthohumults	Humic Luvisol	Humic Ferric Lixisol	Alfisols	Soils Ferrugineux Tropicaux Lessives	Lm
We	2000	Typic Plinthaquox	Plinthic Gleysol	Plinthic Gleysol	Various	Soils Hydromorphes	Cl
Ka[7]	1000	Typic endoaquept	Gleyic Gleysol	Gleyic Humic Gleysol	Various	Soils Hydromorphes	Cl
Total soil types:						7	

[1] SA = South Africa
[2] United State Department of Agriculture (1999). Soil Taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys. Nature Resources Conservation Service. U.S.A.
[3] The Food and Agriculture Organization of the United Nations (1974), FAO-Unesco Soil Classification System
[4] The International Union of Soil Science (1998), World Reference Base Soil Resources
[5] Soil Survey Staff (1998), Keys to Soil Taxonomy. Unite State Washington DC.
[6] Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM) (1974)
[7] No samples were analyzed for this soil type due to shallow (50 cm) water table (flooded profile). Only visual examination was conducted.

A-7: Description of the main soil types occurring in the vicinity of Equatoria Teak plantations (Nzara, South Sudan)

Dresden 2000

Station:	7	Location (UTMZ35, Adindan)		
Profile:	**Y7**	**X**	**Y**	**Z (m.a.s.l.)**
soil classification system:	***[8]SCWG,1991***	***641724***	***513656***	***640***

Brief location description:

Yabua plantation margin, watershed area. Timber harvesting and poor canopy cover results in the grass invation into the gaps within the plantation.

Profile Y7	Horizon	Depth	Brief description	Gravel %	Clay %	Texture	N %	Org C %	C/N
	A1	0-10	Orthic A, well-rooted, weak to moderate structure, dark reddish-brown	13	32	SaClLm	0.05	0.76	16
	AB	10-35	Transitional horizon with pea iron, dark-reddish brown with frequent hich-chroma concretions	58	30	SaClLm	0.04	0.54	14
	Bplh	35-55	Hard plinthic, very poor root penetration, strongly cemented high-chroma iron concretions.						

[8] Soil Classification Working Group of South Africa (1991)

Nomanci 1100

Station:	1	Location (UTMZ35 Adindan)		
Profile:	**Y1**	**X**	**Y**	**Z (m.a.s.l)**
Soil classifica-tion system:	***SCWG (1991)***	***644357***	***512314***	***653***

Brief location description:

Yabua plantation, watershed area, laterite outcrops, grasses in the understorey. Such presence may be a result of poor canopy closure on these shallow soils or recent wood extraction. Recent sediment on laterite, probably from termitarium weathering.

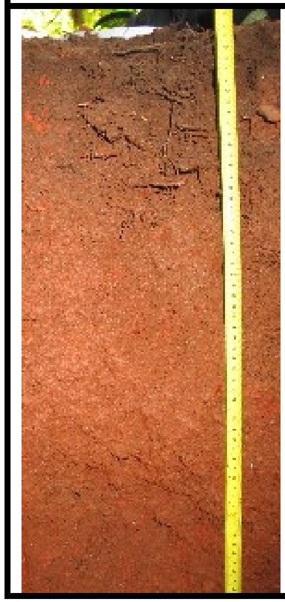
Profile Y1	Horizon	Depth	Brief description	Clay %	Texture	Gravel, %	N %	Org C %	C/N
	A1	0-10	Humic A. Moderately strong structure, well-rooted. Dark brown. Recent sediment.	51	SaCl	13	0.17	1.73	10
	AB	10-15	Neocutanic horizon with high proportion of pea iron concretions (Lithocutanic)	36	SaClLm	20	0.12	1.53	13
	Bplh	15-38	Lithocutanic: fractured hard plinthic, poor root penetration, high cementation with iron.		Cl				

Inanda 1200

Station:	4	Location (UTMZ35, Adindan)		
Profile:	Y4	X	Y	Z (m.a.s.l.)
Soil classification system:	*SCWG, 1991*	*641360*	*513474*	*604*

Brief location description:

Yabua plantation, lower part of the watershed area. Old bush fallow, presumably in the forest reserve area.

Profile Y4	Horizon	Depth	Brief description	Gravel %	Clay %	Texture	N %	Org C %	C/N
	A	0-20	Humic A, soft well-structured dark red-brown.	14	34	SaClLm	0.14	2.00	14
	Btf	20-40	Luvic, ferric red apedal B, frequent concretions (pea iron) forming most of gravel fraction.	74	44	SaCl	0.09	1.17	13
	Bf	40-60	Ferric red apedal B lighter-textured gravelly material	74	29	SaCl	0.05	0.64	12
	Bl	60-100	Lithocutanic B – transitional to parent material with common large fragements of laterite.	67	23	Lm	0.04	0.40	11

Sweetwaterf 1120

Station:	23	Location (UTMZ35, Adindan)		
Profile:	**M11**	**X**	**Y**	**Z (m.a.s.l.)**
Soil classification system:	*SSSA,1991*	*639149*	*511579*	*625*

Brief location desciption:

Mabarizanga area. First terrace. Recently burnt patch of agricultural land.

Profile	Horizon	Depth	Brief description	Gravel, %	Clay %	Texture	N %	Org C %	C/N
	0s	0-2	Surface sediment	14	46	SaCl	0.12	2.17	18
	A	2-15	Orthic A, dark-reddish-brown with some concretions in gravel fraction.	22	30	SaClLm	0.13	1.98	15
	AB	15-20	Transitional horizon to clay –illuvial	13	31	SaClLm	0.06	0.92	15
	Bt	20-80	Neocutanic B. Clay-illuvial B with pea iron gradually grading into laterite below 80 cm depth. Moderately-strong structure.	13		SaClLm	0.05	0.58	13

Sweetwater 1120

Station:	5	Location (UTMZ35, Adindan)				
Profile:	Y5	X	Y	Z (m.a.s.l.)		
Soil classification system:	*SSSA,1991*	*641502*	*513850*	*612*		**Brief location desciption:** Yabua teak plantation. First terrace.

Profile Y5	Horizon	Depth	Brief description	Gravel %	Clay %	Texture	N %	Org C %	C/N
	A	0-20	Humic A. Very dark brown. Some concretions.	19	25	SaClLm	n/d	n/d	n/d
	Bt	20-60	Luvic neocutanic B. Clay-illuvial B with pea iron gradually grading into laterite below 80 cm depth. Moderately-strong structure.	0	25	Lm	0.05	0.57	11
	BC	60-90	Lithocutanic B. Yellow-brown. Large fragments of laterite, common pea iron concretions.	18	n/d	Lm	0.04	0.36	9
	Cplh	90-120	Laterite (hard plinthic B)	52	44	ClLm	0.04	0.43	10

Westleigh 2000

Station:	26	Location (UTMZ35, Adindan)			Brief location desciption:
Profile:	M14	X	Y	Z (m.a.s.l.)	
soil classification system:	*SSSA,1991*	*639162*	*509249*	*616*	Mabarizanga area: upper floodplain. Tall grassland.

Profile M14	Horizon	Depth	Brief description	Gravel %	Clay %	Texture	N %	Org C %	C/N
	A	0-10	Orthic A with high OM content, dark brown.	30	58	Cl	0.13	2.35	18
	Bpl	10-30	Soft Plinthic B. Stagnic. Yellow-brown material with common pea iron	30	60	Cl	0.09	1.48	16
	Cg	30-80	Gleyic alluvium. Common concretions and low-chroma mottles throughout. Heavy clay.	22	n/d	Cl	0.05	0.50	10

Kroonstad 2000

Station:	3	Location (UTMZ35, Adindan)		
Profile:	Y3	X	Y	Z (m.a.s.l.)
Soil classification system:	*SSSA,1991*	*640927*	*513431*	*600*

Brief location desciption:

Yabua plantation area:
lower floodpoain, close to a running stream. Tall grassland.

Profile	Horizon	Depth	Brief description	Texture
	A	0-10	Orthic A with high organic matter content, very dark brown, heavy clay.	Cl
	Cg	30-50	Gleyic alluvium, heavy clay, low chroma mottles throughout the horizon. Water table at 50 cm.	Cl

A-8: [9]List of Profiles Sampling Method, Maximum Depth and Soil Family and Forms

Station	Site	Max-depth (cm)	Sampling method	Soil Form	Page
1	Y1	38	Pit	Nomanci 1100	92
1	Y1	100	Pit	Nomanci 1200/1100	92
4	Y4	100	Pit	Inanda 1200	93
5	Y5	120	Pit	Sweetwater 1120	87
6	Y6	90	Pit	Inanda 1200	87
7	Y7	55	Pit	Dresden 2000	91
14	Y14	80	Exposure		
23	M11	80	Pit	Sweetwater 1120	88
26	M14	80	Pit	Westleigh 1000	89
28	M16	30	Auger		
30	M18	100	Pit	Sweetwater 1120	88
31	M19	80	Auger		
32	AN1	80	Auger		
33	AN2	55	Auger		
34	AN3	20	Auger		
36	AN5	80	Auger		
37	PN6	120	Pit	Longland 1000	85
38	n/a	40	Auger		
Total profiles analyzed:		**20**			

[9] Only the Pit profiles were assigned to a soil Family and Form.

VII. [e]APPENDIX B-1: SOIL PHYSICAL CHARACTERISTICS

Site	Station	Horizon	Land Use	Depth (cm)	Description	Gravel (%)	Sand Grade	Sand (%)	Clay (%)	Silt (%)	Texture
Y1 A	1	A	Out Plt	0 - 10	Dark-yellowish-brown	51	Coarse	37	57	7	**SaCl**
Y1 AB	1	AB	Out Plt	10 - 15	Reddish-brown	33	Coarse	50	31	19	**SaClLm**
Y1 Bphl	1	Bphl	Out Plt	15 - 38	Reddish-brown	69	Coarse	38	52	10	**Cl**
Y4 A	4	A	Out Plt	20 - 40	Reddish-brown	74	Coarse	53	43	4	**SaCl**
Y4 Bft	4	Bft	Out Plt	40 - 60	Yellowish-red	74	Coarse	58	34	8	**SaClLm**
Y4 Bph	4	Bph	Out Plt	60 - 100	Red	67	Coarse	49	32	18	**SaClLm**
Y6 Sand S	6	Os	Out Plt	0 - 1	Dark-yellowish-brown	6	Medium	77	22	2	**SaClLm**
Y6 A	6	A	Out Plt	0 - 30	Dark-brown	13	Medium	61	36	4	**SaClLm**
Y14 A	14	A	Out Plt	0 - 30	Dark-brown	30	Coarse	63	30	7	**SaClLm**
Ma11 A1	23	Os	Out Plt	0 - 2	Dark-grayish-brown	14	Medium	51	43	6	**SaCl**
Ma11 A2	23	A2	Out Plt	2 - 15	Dark-brown	22	Medium	60	29	11	**SaClLm**
Ma11 AB	23	AB	Out Plt	15 - 20	Dark-yellowish-brown	13	Medium	60	35	6	**SaClLm**
Ma14 A	26	A	Out Plt	0 - 10	Dark-grayish-brown	30	Fine	37	58	5	**Cl**
Ma14 B	26	B	Out Plt	10 - 30	Yellowish-brown	30	Fine	28	58	14	**Cl**
Ma14 Cg	26	Cg	Out Plt	30 - 80	Light-yellowish-brown	22	Fine	27	56	18	**Cl**
Ma16 A	28	A	Out Plt	0 - 10	Dark-brown	11	Fine	65	33	3	**SaClLm**
Ma16 B	28	B	Out Plt	10 - 30	Yellowish-red	23	Fine	50	46	5	**SaCl**
Ma 17 Sand	29	Os	Out Plt	0 - 2	Brownish-yellow	30	Coarse	34	62	4	**Cl**
Ma18 A	30	A	Out Plt	0 - 15	Very dark grayish-brown	8	Coarse	67	29	4	**SaClLm**
Ma18 B	30	B	Out Plt	15 - 60	Very dark grayish-brown	11	Coarse	58	39	3	**SaCl**
Ma18 C	30	C	Out Plt	70 - 100	Gray	9	Coarse	84	15	1	**LmSa**
AN A	32	A	Out Plt	0 - 10	Gray	7	Coarse	79	17	3	**SaLm**
AN1 B	32	B	Out Plt	60 - 80	Grayish-brown	8	Coarse	73	24	3	**SaClLm**

[e] Out Plt = Outside plantation; Cl = Clay; Sa = Sandy; Lm = Loam; Bf = B horizon with fermented material, Bph = B horizon with hard plinthite.

[f]APPENDIX B-2: SOIL PHYSICAL CHARACTERISTICS

						Gravel	Sand		Clay	Silt	
Site	Station	Horizon	Land Use	Depth (cm)	Description	(%)	Grade	(%)	(%)	(%)	Texture
AN3 A	34	A	Out Plt	0 - 20	Dark-grayish-brown	13	Coarse	58	38	4	**SaCl**
AN2 B	33	B	Out Plt	40 - 55	Yellowish-brown	22	Coarse	50	46	5	**SaCl**
AN5 A	36	A	Out Plt	0 - 5	Dark-reddish-brown	20	Coarse	49	49	2	**SaCl**
AN5 AB	36	AB	Out Plt	10 - 20	Dark-reddish-brown	71	Coarse	51	44	5	**SaCl**
AN5 B	36	B	Out Plt	60 - 80	Reddish-brown	62	Coarse	61	26	13	**SaClLm**
Y6A Sand	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Y6 B	6	B	Out Plt	30 - 50	Dark-brown	25	Medium	59	35	6	**SaClLm**
Y5 A	5	A	In Plt	0 - 20	Grayish-brown	19	Medium	71	26	3	**SaClLm**
Y5 B	5	B	In Plt	20 - 60	Light-yellowish-brown	0	Medium	54	33	13	**SaClLm**
Y5 C	5	C	In Plt	60 - 90	Light-yellowish-brown	18	Medium	40	53	7	**Cl**
Y5 Cp	5	Cp	In Plt	100 - 120	Light-yellowish-brown	52	Coarse	43	45	12	**Cl**
Y7 A1	7	A	In Plt	0 - 35	Dark-brown	13	Medium	64	28	8	**SaClLm**
Y7 B	7	B	In Plt	35 - 55	Dark-brown	58	Coarse	67	30	3	**SaClLm**
Y13 A	13	A	Inplt	0-15	Dark-brown	44	Coarse	41	55	4	**Cl**
Y13 B	13	B	In Plt	15 - 45	Strong brown	26	Coarse	38	46	17	**Cl**
Y8 A	8	A	In Plt	20 - 40	Dark-brown	14	Medium	68	31	1	**SaClLm**
Y8 B	8	B	In Plt	40 - 75	Dark-brown	16	Medium	65	35	1	**SaClLm**
Y8 C	8	C	In Plt	75 - 100	Strong brown	16	Medium	64	26	11	**SaClLm**

[f] In Plt = Inside plantation; Out plt and In plant = Out of and Inside plantations; Sa = Sandy; Cl = Clay; Lm = Loam

[g]APPENDIX B-3: SOIL PHYSICAL CHARACTERISTICS

Site	Station	Horizon	Land Use	Depth (cm)	Description	Gravel (%)	Sand Grade	Sand (%)	Clay (%)	Silt (%)	Texture
Ma19 OSand	31	Os	In Plt	0 - 1	Dark-brown	3	Medium	78	19	3	**SaLm**
Ma19 A1	31	A	In Plt	1 - 20	Dark-brown	21	Coarse	65	31	4	**SaClLm**
Ma19 B1	31	B1	In Plt	20 - 40	Dark-yellowish-brown	18	Coarse	54	44	2	**SaCl**
Ma19 B2	31	B2	In Plt	40 - 80	Strong brown	10	Coarse	41	49	10	**Cl**
PN6 Termite	37	nd	In Plt	nd	Grayish-brown	16	Medium	68	29	3	**SaClLm**
PN6 Sand Str	37	nd	In Plt	0 - 1	Dark-yellowish-brown	24	Coarse	74	24	1	**SaClLm**
PN6 A1	37	A1	In Plt	0 - 7	Dark-grayish	10	Coarse	65	28	8	**SaClLm**
PN6 A2	37	A2	In Plt	7 - 20	Dark-grayish	10	Coarse	57	27	16	**SaClLm**
PN6 B	37	B	In Plt	20 - 57	Light-gray	14	Coarse	70	24	6	**SaClLm**
PN6 Btf	37	Btf	In Plt	57 - 70	Light-gray	0	Coarse	70	23	7	**SaClLm**
PN6 Btf	37	Btf	In Plt	70 - 90	Dark-brown	74	Coarse	84	13	3	**LmSa**
PN6 A	37	A	In Plt	70 - 90	Grayish-brown	11	Fine	57	36	7	**SaCl**
AN7 OSand	38	Os	In Plt	0 - 2	Dark-yellowish-brown	nd	Fine	79	19	2	**SaLm**
AN7 A	38	A	In Plt	2 - 10	Dark-brown	14	Fine	63	34	3	**SaClLm**
AN7 Bf	38	Btf	In Plt	20 - 30	Dark-brown	24	Fine	54	40	6	**SaCl**
AN7 Bfr	38	Bf	In Plt	30 - 40	Dark-brown	40	Coarse	58	40	2	**SaCl**

[g] In plt = = Inside teak plantations; Str = Stone line reduced; Btf = B horizon with clay increase than above horizon and with fermented material (Young, 1976)

VIII. [1]APPENDIX C

C-1: SOIL CHEMICAL CHARACTERISTICS: pHs, Acidity Organic, Carbon, Nitrogen, C/N ratio.

Site	Station	Horizon	Land Use	Depth (cm)	$pH_{(water)}$	$pH_{(KCl)}$	H^+ %	Al^{3+} %	Org C %	N %	C/N
Y1 A	1	A	Out Plt	0 - 10	5.38	3.98	27	32	1.73	0.17	10
Y1 AB	1	AB	Out Plt	10 - 15	4.98	3.99	45	49	1.53	0.12	13
Y1 Bphl	1	Bphl	Out Plt	15 - 38	nd	nd	nd	nd	0.79	0.07	11
Y4 A	14	A	Out Plt	0 - 30	7.16	6.24	nd	nd	3.23	0.33	10
Y4 A	4	A	Out Plt	20 - 40	6.12	4.51	nd	nd	1.17	0.09	13
Y4 Bft	4	Bft	Out Plt	40 - 60	5.59	4.14	nd	nd	0.64	0.05	12
Y4 Bph	4	Bph	Out Plt	60 - 100	5.54	4.35	nd	nd	0.40	0.04	11
Y6 SandStr	6	Os	Out Plt	0 - 1	6.17	5.98	nd	nd	0.92	0.06	16
Y6 A	6	A	Out Plt	0 - 30	6.09	4.98	nd	nd	1.31	0.08	16
Ma11 A1	23	Os	Out Plt	0 - 2	5.89	5.29	nd	nd	2.17	0.12	18
Ma11 A2	23	A2	Out Plt	2 - 15	5.82	4.46	nd	8.14	1.98	0.13	15
Ma11 AB	23	AB	Out Plt	15 - 20	4.94	3.95	37.91	42.46	0.92	0.06	15
Ma14 A	26	A	Out Plt	0 - 10	5.94	4.56	nd	nd	2.35	0.13	18
Ma14 B	26	B	Out Plt	10 - 30	5.10	4.05	20.03	26.71	1.48	0.09	16
Ma14 Cg	26	Cg	Out Plt	30 - 80	4.96	4.01	28.60	34.73	0.50	0.05	10
Ma16 A	28	A	Out Plt	0 - 10	5.86	4.94	nd	nd	1.06	0.07	14
Ma16 B	28	B	Out Plt	10 - 30	5.30	3.91	41.34	46.51	0.90	0.09	10
Ma 17 Sand	29	Os	Out Plt	0 - 2	4.56	4.06	45.14	46.86	0.33	0.04	9
Ma18 A	30	A	Out Plt	0 - 15	6.53	5.98	nd	nd	2.90	0.18	16
Ma18 B	30	B	Out Plt	15 - 60	5.98	4.95	nd	nd	1.76	0.11	16
Ma18 C	30	C	Out Plt	70 - 100	5.96	4.65	nd	nd	0.37	0.03	15
AN1A	32	A	Out Plt	0 - 10	6.43	5.50	nd	nd	0.79	0.05	15
AN1 B	32	B	Out Plt	60 - 80	4.26	3.82	43.13	48.76	0.43	0.04	12
AN2B	33	B	Out Plt	40 - 55	5.46	3.88	34.05	40.43	0.49	0.04	13
AN3 A	34	A	Out Plt	0 - 20	6.57	5.65	nd	nd	1.45	0.09	16
AN5 A	36	A	Out Plt	0 - 5	6.58	5.59	nd	nd	4.54	0.34	13
AN5 AB	36	AB	Out Plt	10 - 20	5.64	4.44	nd	nd	2.37	0.13	18
AN5 B	36	B	Out Plt	60 - 80	6.39	4.78	nd	nd	1.09	0.07	16

[1] Os = Organic with accumulation of sesquioxides; Cg = gleyed, concreted mottle; Bt = with more clay than above horizon; nd = not applicable; Org C = Organic carbon, C/N = Carbon/ Nitrogen; Str = Stratified, phl = hard plinthite

[2]C-2: SOIL CHEMICAL CHARACTERISTICS: pHs, Acidity Organic, Carbon, Nitrogen, C/N ratio

Site	Station	Horizon	Land Use	Depth (cm)	$pH_{(water)}$	$pH_{(KCl)}$	H^+ %	Al^{3+} %	Org C %	N %	C/N
Ma19 A	31	A	In plt	1-20	5.91	4.99	nd	nd	0.85	0.05	18
Ma19 B1	31	B1	In plt	20-40	5.37	3.97	27.31	33.17	1.22	0.07	18
Ma19 B2	31	B2	In plt	40-80	4.93	4.09	22.96	31.58	0.61	0.05	12
PN6 Termite	37	nd	In Plt	nd	5.16	4.13	11.19	22.39	1.01	0.07	14
PN6 Sand Str	37	Os	In Plt	0 - 1	6.42	5.4	nd	nd	0.36	0.05	7
PN6 A1	37	A1	In Plt	0 - 7	4.93	3.87	3.87	39.30	0.64	0.05	13
PN6 A2	37	A2	In Plt	7 - 20	5.08	3.82	3.82	38.80	0.68	0.06	11
PN6 A	37	A	In Plt	20 - 57	5.42	3.9	3.90	28.15	0.22	0.04	6
PN6 Btf	37	Btf	In Plt	57 - 70	5.6	3.98	3.98	31.19	0.24	0.05	5
PN6 Bfr	37	Bfr	In Plt	70 - 90	5.49	4.31	nd	nd	0.35	0.03	14
PN6 A	37	A	In Plt	70 - 90	5.68	4.25	4.25	0.00	1.05	0.08	13
AN7 OSand	38	Os	In Plt	0 - 2	6.61	6.14	nd	nd	0.52	0.06	9
AN7 A	38	A	In Plt	2 - 10	6.25	5.05	nd	nd	1.42	0.07	21
AN7 Btf	38	Btf	In Plt	20 - 30	4.72	3.98	3.98	41.06	0.80	0.05	16
AN7 Bfr	38	Bfr	In Plt	30 - 40	5.16	3.98	3.98	41.69	0.43	0.04	11
Y5 A	5	A	In Plt	0 - 20	5.82	4.69	nd	nd	0.33	0.04	8
Y5 B	5	B	In Plt	20 - 60	5.18	3.82	37.66	42.01	0.57	0.05	11
Y5 C	5	C	In Plt	60 - 90	4.94	3.94	39.16	43.68	0.36	0.04	9
Y5 Cp	5	Cp	In Plt	100 - 120	5.07	4.04	34.33	41.19	0.43	0.04	10
Y7 A	7	A	In Plt	0 - 35	5.61	4.53	nd	nd	0.76	0.05	16
Y7 B	7	B	In Plt	35 - 55	5.25	3.94	41.28	46.44	0.54	0.04	14
Y13 A	13	A	In Plt	0 - 15	6.43	5.35	nd	nd	2.80	0.16	18
Y13 B	13	B	In Plt	15 - 45	6.06	5.25	nd	nd	0.96	0.08	12
Y8 A	8	A2	In Plt	20 - 40	5.87	5.36	nd	nd	1.07	0.07	16
Y8 B	8	B	In Plt	40 - 75	6.3	4.83	nd	nd	0.51	0.04	12
Y8 C	8	C	In Plt	75 - 100	5.85	4.13	nd	nd	0.51	0.04	13

[2] Os = Organic with accumulation of sesquioxides; Cg = gleyed, concreted mottle; Bt = with more clay than above horizon; nd = not applicable; Org C = Organic carbon, C/N = Carbon/ Nitrogen; Cp = C horizon with presence of plinthite; Bfr = B horizon with fermentation sign; Str = Stratified. H^+ and Al^{3+} are expressed as % and not as cmolc/kg so compare their values with %C and %N they are supposed to result from organic matter decomposition or soil parent materials

[3]C-3: SOIL CHEMICAL CHARACTERISTICS: Al%, Fe% Fe/Al, Available P, Total P, TotP/AvP, S-val

Site	Station	Horizon	Land Use	Depth (cm)	Al(mg/kg) amorphous +crystalline	Fe(mg/kg) amorphous +crystalline	Fe/Al	AvP mg/kg	TotP mg/kg	Tp/Ap	S-value $cmol_{(+)}/kg$
PN6 Sand Str	37	nd	In Plt	0 - 1	0.006	0.01	1.6	0.1	1.8	0.2	1.68
PN6 A1	37	A1	In Plt	0 - 7	0.001	0.002	1.6	nd	3.4	0.3	1.01
PN6 A2	37	A2	In Plt	7 - 20	0.003	0.011	3.3	0.1	3.0	0.3	1.04
PN6 A	37	A	In Plt	20 - 57	0.002	0.007	3.4	0.1	1.8	0.2	0.80
PN6 Btf	37	Btf	In Plt	57 - 70	0.001	0.001	0.5	0.1	1.0	0.1	1.02
PN6 Bf	37	Bf	In Plt	70 - 90	0.01	0.047	4.8	0.1	2.2	0.2	1.08
AN7 OSand	38	Os	In Plt	0 - 2	0.008	0.067	8.6	0.2	2.0	0.2	2.67
AN7 A	38	A	In Plt	2 - 10	0.005	0.028	5.7	0.1	4.4	0.4	4.48
AN7 Bf	38	Btf	In Plt	20 - 30	0.007	0.036	4.9	0.1	1.4	0.1	1.31
AN7 Bfr	38	Bf	In Plt	30 - 40	0.008	0.07	8.9	0.1	4.6	0.5	0.90
Y5 A	5	A	In Plt	0 - 20	0.003	0.02	6.0	0.2	2.6	17.3	2.46
Y5 B	5	B	In Plt	20 - 60	0.003	0.021	6.2	0.1	5.4	108.0	1.84
Y5 C	5	C	In Plt	60 - 90	0.005	0.006	1.3	0.2	0.8	5.3	1.48
Y5 Cp	5	Cp	In Plt	100 - 120	0.004	0.027	6.4	0.0	2.2	110.0	1.38
Y7 A	7	A	In Plt	0 - 35	0.003	0.01	3.4	0.1	5.2	40.0	2.28
Y7 B	7	B	In Plt	35 - 55	0.006	0.032	5.0	0.1	3.8	31.7	0.91
Y13 A	13	A	In Plt	0 - 15	0.001	0.01	1.1	0.2	12.2	61.0	9.60
Y13 B	13	B	In Plt	15 - 45	0.008	0.04	5.2	0.1	6.2	44.3	5.40
Y8 A	8	A2	In Plt	20 - 40	0.005	0.035	6.4	0.1	3.0	25.0	4.88
Y8 B	8	B	In Plt	40 - 75	0.004	0.031	8.4	0.1	4.4	73.3	3.29
Y8 C	8	C	In Plt	75 - 100	0.003	0.018	6.8	0.1	3.0	27.3	2.31
Ma19 OSand	31	Os	In Plt	0 - 1	0.008	0.063	7.5	0.3	2.4	8.0	4.65
Ma19 A	31	A	In Plt	1 - 20	0.005	0.043	7.9	0.1	8.8	176.0	5.91
Ma19 B1	31	B1	In Plt	20 - 40	0.006	0.036	5.7	0.1	7.0	50.0	2.67
Ma19 B2	31	B2	In Plt	40 - 80	0.002	0.003	1.5	0.0	2.4	240.0	2.09
PN6 Termite	37	nd	In Plt	nd	0.003	0.016	5.2	0.3	2.8	9.0	2.34

[3] S-value = $\sum(Na^{+} + Mg^{2+} + K^{+} + Ca^{2+})$ in $1MNH_4OA_C$ pH 7; AvP or Ap = Available Phosphorous; TotP or Tp = Total Phosphorous; Str = Stratified; Bt = with more clay than above horizon; nd = not applicable; Bfr = B horizon with fermentation sign; Str = Stratified.

C-4: SOIL CHEMICAL CHARACTERISTICS: Al, Fe, Fe/Al, Available P, Total P, TotP/Av, S-value.

Site	Station	Horizon	Land Use	Depth (cm)	Al(mg/kg) amorphous +crystalline	Fe(mg/kg) amorphous +crystalline	Fe/Al	AvP mg/kg	TotP mg/kg	Tp/Ap	S-value $cmol_{(+)}/kg$
Y1 A	1	A	Out Plt	0 - 10	0.0	0.0	1.8	0.7	14.2	19.2	10.91
Y1 AB	1	B	Out Plt	10 - 15	0.0	0.0	1.3	0.2	11.0	64.7	7.97
Y1 Bphl	1	Bphl	Out Plt	15 - 38	0.008	0.029	3.9	0.2	7.2	30.0	5.34
Y4 A	14	A	Out Plt	0 - 30	0.006	0.043	7.4	0.2	4.8	28.2	10.14
Y4 A	4	A	Out Plt	20 - 40	0.001	0.003	2.2	0.1	5.4	45.0	3.06
Y4 Bft	4	Bft	Out Plt	40 - 60	0.001	0.008	5.8	0.1	9.4	104.4	1.73
Y4 Bt	4	Bt	Out Plt	60 - 100	0.001	0.0	0.3	0.1	10.8	135.0	1.24
Y6 Sand S	6	Os	Out Plt	0 - 1	0.01	0.063	6.3	0.3	3.4	12.1	3.43
Y6 A	6	A	Out Plt	0 - 30	0.007	0.048	7.3	0.2	2.4	14.1	3.84
Y6 B	6	B	Out Plt	30 - 50	0.006	0.049	7.8	0.0	1.6	53.3	1.34
Ma11 A1	23	Os	Out Plt	0 - 2	0.0	0.0	0.3	0.8	13.2	16.5	6.38
Ma11 A2	23	A2	Out Plt	2 - 15	0.007	0.04	5.8	0.2	3.4	20.0	2.99
Ma11 AB	23	AB	Out Plt	15 - 20	0.004	0.002	0.6	0.2	5.2	27.4	1.68
Ma14 A	26	A	Out Plt	0 - 10	0.005	0.03	6.4	0.2	14.8	67.3	4.97
Ma14 B	26	B	Out Plt	10 - 30	0.0	0.001	7.1	0.1	6.4	91.4	3.15
Ma14 CG	26	Cg	Out Plt	30 - 80	0.007	0.014	2.0	0.0	0.8	80.0	2.37
Ma16 A	28	A	Out Plt	0 - 10	0.006	0.057	9.4	0.2	6.6	41.3	2.63
Ma16 B	28	B	Out Plt	10 - 30	0.003	0.014	4.4	0.1	7.6	63.3	0.90
Ma 17 Sand	29	Os	Out Plt	0 - 2	0.002	0.001	1.0	0.0	2.0	100.0	1.84
AN2B	33	B	Out Plt	40 - 55	0.004	0.027	7.5	0.1	4.2	32.3	1.57
AN5 A	36	A	Out Plt	0 - 5	0.002	0.002	1.0	0.3	16.6	50.3	14.05
AN3 A	34	A	Out Plt	0 - 20	0.003	0.015	5.0	0.3	10.4	40.0	5.32
AN5 AB	36	AB	Out Plt	10 - 20	0.0	0.001	4.6	0.1	7.0	116.7	4.59
AN5 B	36	B	Out Plt	60 - 80	0.003	0.002	0.9	0.1	12.8	128.0	3.91
Ma18 A	30	A	Out Plt	0-15	0.008	0.003	0.4	0.3	12	37.5	9.85
Ma18B	30	B	Out plt	15-60	0.004	0.037	8.7	0.1	3.6	60.0	5.97
Ma18 C	30	C	Out plt	70-100	0.002	0.005	2.2	0.2	0.8	3.5	2.07
AN1A	32	A	Out Plt	0-10	0.002	0.007	4.3	0.3	2.6	9.0	2.66
AN1 B	32	B	Out Plt	60 - 80	0.004	0.004	1.0	0.2	2.4	13.3	0.54

C-5: Metric conversion from mg/kg to kg/ha (Adapted from: Juma, N.C: http://www.soils.rr.ualberta.ca/Pedosphere/content/section03/page03_03.cfm, retrieved January 22, 1999)

Textural Class	Bulk Density ($Mg/m^3 = g/cm^3$)	Porosity (%)	Example of calculation from (3 ppm: mg/kg to kg/ha)
Sand	1.55	42	• Horizon length: 1m • Horizon texture = Sandy-Loam; Bulk density = $1.4 g/cm^3$ = $1.4x1000 kg/m^3$ • 1ha = $10,000m^2$ ♦ Horizon volume = 1m x $10,000m^2$ = $10,000m^3$ ♦ Horizon mass = 1.4x1000x10,000 = 14,000,000kg ♦ Nutrient status in kg/ha = 1,400,000kg x 3ppm (mg/kg) = 4,200,000mg/ha = 4,200kg/ha.
Sandy loam	1.40	48	
Fine sandy loam	1.30	51	
Loam	1.20	55	
Silt loam	1.15	56	
Clay loam	1.10	59	
Clay	1.05	60	
Aggregated clay	1.00	62	

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