SOIL PHOSPHORUS AVAILABILITY IN SELECTED SAO HILL FOREST PLANTATIONS, IRINGA, TANZANIA

BY

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ABSTRACT

A study was undertaken to investigate soil phosphorus availability in selected Sao Hill Forest Plantations located in Iringa region, Tanzania. Pine and Eucalyptus are the major species in Sao Hill Forest Project. Soil samples were collected from three adjacent stands of pine, eucalyptus and pine-eucalyptus mixture and analysed for physical and chemical properties. Composite top soil samples were collected from each stand at a depth of 0 to 20 cm and used for bioassay experiment in which three levels of N and four levels of P were factorially arranged. *Eucalyptus saligna* seeds were directly sown into pots containing 1.8 kg of soil (Oven dry weight), watered to 60% field capacity for the rest of the growth period (12 weeks). The soil samples before and after the experiment were extracted with different extractants to estimate available P. The soil samples were also subjected to a fractionation procedure to estimate the amount of P in different pools. Soil analysis results showed that the soils were strongly acidic (pH $_{CaCl_2}$ 4.2 to 4.5). The soil exchange sites were dominated by aluminium (33%) and the soils were deficient in P (< 10 mg P kg^{-1}). The amount of P extracted by Resin, Bray 1, Bray 2 and iron oxide filter strips were significantly ($P < 0.05$) affected by P fertilizers. Iron oxide filter paper strips extracted the highest amount of P at any P rate, followed by the Resin method. Plant P uptake was significantly and highly correlated with Bray-2-P ($r=0.70$), resin P ($r=0.64$), Bray-1-P ($r=0.63$) and iron oxide filter strips ($r=0.59$). The results indicated that in the untreated soils, adsorption maximum was lower in the mixed stand but this stand had the highest bonding energy. The potential buffering capacity was lowest in eucalyptus stand. The adsorption maximum was little affected by fertilizer amendments while as expected the bonding energy decreased with increasing fertilizer rate. Most of the added P was recovered as $NaHCO_3$-P_o fraction accounting for 43% in the pine stand and 40% in the mixed stand. In the eucalyptus stand. 27% of the applied P was recovered as $NaHCO_3$-P_i and to 25% as $NaHCO_3$-P_o. Most of the extraction methods correlated well with at least one of the soil fractions. The application of P fertilizers had a significant ($P<0.05$) effect on seedling height in the soils from all the stands but the height measured at the 9th week (H3) showed a significant interaction between soil type and applied P fertilizer. Root collar diameter. total and components dry matter of eucalyptus seedlings were significantly different ($P<0.05$) at different levels of P fertilizer. Total and components P contents were significantly ($P<0.05$) affected by P fertilization and also there was a significant interaction between soil source and P fertilizer. The soils from different stands significantly ($P<0.05$) affected foliar P concentration of *E. saligna* seedlings indicating that the pine stand was P deficient. Application of N and P fertilizers to *E. saligna* significantly increased N and P foliar concentrations and there was a strong positive correlation between foliar P concentration and growth variables confirming P deficiency. It is concluded that the acid soils of Sao Hill are severely P deficient and that application of P fertilizers is likely to improve growth and yield of forest plantations in the Project.

DECLARATION

I VENDELINE EMMANUEL TAIRO do hereby declare to the Senate of Sokoine University of Agriculture that the work presented here is my original work and that it has not been submitted for a higher degree in any other University.

Signature...

Date...

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DEDICATION

This work is dedicated to my parents who tirelessly laid the foundation of my education.

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ABBREVIATIONS

a. s.l.	above sea level
BD	Bulk density
Ca	Calcium
CEC	Cation exchange capacity
ECEC	Effective cation exchange capacity
cm	centimeter
E	east
S	south
FAO	Food and Agriculture Organization
g	gramme
mg	milligramme
ha	hactare
K	potasium
m	metre
MC	moisture content
mm	millimetre
Na	sodium
ns	not significant
OC	organic carbon
ppm	part per million
SAS	statistical analysis system
SUA	Sokoine University of Agriculture

SYMBOLS

°C	Degree centigrade
°E	Degree East
°S	Degree south
<	Less than
>	Greater than
%	Percent
=	Equal to
≥	Greater than or equal to
≤	Less than or equal to

CHAPTER ONE

1. INTRODUCTION

Forest plantations in Tanzania cover over 150,000 ha (Mtuy, 1996) and play an important role in the national economy as a source of raw materials for wood-based industries whose products earn local and foreign currency. They also supply other wood products (fuel wood and poles) and provide employment in rural areas. In the recent past, over 80% of the industrial forest plantations were state-owned of which 50% are in Sao Hill alone. The major species planted in the Sao Hill include *Pinus patula* (31,439 ha), *P. caribaea* (1,041 ha), *P. elliottii* (4,183 ha), *Eucalyptus grandis*, *E. saligna*, *E. maidenii* (3,985 ha) and *Cupressus lusitanica* (Mgeni, 1986). The Sao Hill Forest Project is mainly meant to cater for a sawmill and a pulp and paper mill which can annually use 45,000m^3 and 300,000m^3 of wood, respectively (Mhando *et al.*, 1993; Tangwa *et al.*, 1993)

During the first rotation, plantation yield varied from 25 to 35 m^3 ha^{-1} year^{-1} for pines and cypress and 30 m^3 ha^{-1} year^{-1} for *Eucalyptus* (Ahlback, 1988). These yields were achieved by using appropriate species/provenances selected from earlier introduction trials, planting on good quality sites, low annual planting target and adequate tending operations (Maliondo and Chamshama, 1996). At present, most of the forest plantations in Tanzania are in the second rotation and there are indications that yields are declining (Tangwa *et al.*, 1988). The possible reasons cited for low productivity during the second rotation include loss of nutrients due to logging and burning of logging slash which result in substantial loss of nutrients such as N, P and S (Procter, 1967; Mhando *et al.*, 1993), soil erosion resulting from exposure of soil by burning and stand establishment techniques involving *taungya* (Maliondo and Chamshama, 1996), soil compaction due to mechanized logging operations during the wet season (Maganga and Chamshama, 1988), loss of nutrients removed in harvested crop biomass during *taungya*, nutrient losses due to leaching of mineralized nutrients and uneven distribution of nutrients caused by windrowing which may leave pockets of poor nutrients (Maliondo and Chamshama, 1996).

In Sao Hill forest plantation, several reports have indicated soil fertility problems during the first rotation (Cannon, 1985). The commonly deficient nutrients are P, N and B (Procter, 1967; Mhando *et al.*, 1993) among others. It is likely that soil fertility problems will become more serious in the subsequent rotations as nutrients are depleted through consecutive harvesting and nutrient lost during plantation establishment (Maliondo and Chamshama, 1996). In old soils such as Oxisols and Ultisols (Nykvist, 1976), nutrients replenishment through soil mineral weathering will not be sufficient to sustain the high growth rates since the soils are highly P defficient. Many studies have recommended supplementation of soil nutrients through fertilization (Procter, 1967; Birk and Turner, 1992; Mhando *et al.*, 1993).

Forest fertilization is one of the exciting and promising developments in forest technology (Schonou and Herbert, 1989). Most of the N and P fertilizer experiments in South Africa, Brazil and Australia have shown substantial increase in crop yield. A strong evidence was presented by Schonou and Herbert (1989) that fertilization of *E. grandis* in different areas of S. Africa, gave additional timber at harvest (10 years) of 25 to 98 m^3 ha^{-1} with a mean of 57 m^3 ha^{-1}, and real return on investment of 25% per ha per year. Another trial in Australia on the same species showed very promising results after six years whereby fertilization increased mechantable volume from 165 m^3 ha^{-1} in the control to 180 m^3 ha^{-1} and further addition of insecticides and herbicides gave 307 m^3 ha^{-1} (Birk and Turner. 1992). Other reports by Schonou and Herbert (1989) showed that fertilization could shorten the period required to reach canopy closure as well as rotational maturity on well-prepared sites. Studies conducted at Sao Hill by Mhando *et al.* (1993) reported that site preparation and fertilization improved the survival and growth of *E. grandis*. Application of N,P,K or B to various tillage treatments improved early growth compared with unfertilized tillage treatments. Despite the significant results indicated by Mhando *et al.* (1993), of response to combined application of N. P and K. it is not clear which nutrient element elicited the response.

In Sao Hill plantations, the major soil types are highly weathered and acidic in nature (Nykvist. 1976). This condition has been reported to influence the availability of P which is the most limiting nutrient apart from N and B (Procter, 1967). The highly weathered acidic soils have low total and available P content, and a high P retention capacity. Many studies have recommended using P fertilizers to replenish the deficient P as it is well known that P deficient soils give high growth responses to P fertilization (Youngberg and Davey. 1968). It is likely that in the acid soils of the Sao Hill forest plantation P fertilization may improve the growth and yield of forest crops. Consequently there is need for evaluating the P status of forest soils, so that the quantity of P needed as fertilizer may be determined. Despite the fact that the importance of P and other nutrients in forest soils is widely recognised, little information is available on P availability in Tanzania forest plantations. Keith *et al.* (1997) reported that many studies on P availability have been conducted in different forest plantation especially on soil P status after silvicultural treatments, extent of P uptake by plants, appropriate methods for estimating P content, pools of P availability among others.

Although various fertility studies have been conducted in Sao Hill Forest Plantation to improve yield (Procter, 1967; Kalaghe and Manssy, 1989; Tangwa *et al.*, 1988; Mhando *et al.*, 1993), none of the studies have attempted to assess the effect of different nutrients applied singly. Therefore, this study is intended to characterize P availability and a significant role of N of the selected soils of Sao Hill Forest Plantation, in order to provide useful information for enhancing long-term maintenance of soil fertility and hence increasing forest plantation yield.

1.1 Main objective

The main objective of this study was to study soil P availability and response to N fertilization as a possible measure of improving yields of Sao Hill Forest Plantation.

1.2 Specific objectives

-To determine P availability of the selected soils in Sao Hill Forest Plantation.

-To compare different methods of estimating P-availability

-To relate P availability indices to P uptake by *Eucalyptus saligna*

-To determine the responses to P and N fertilizers of soils from three stands in Sao Hill Forest Plantation.

-To determine if there is any interaction between Na and P fertilizers in the Sao Hill forest stands.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Soil Fertility Status in Forest Plantations

Generally, few forest soils provide an optimum supply of nutrients for plant growth. Sometimes the marked deficiencies may exist because of improper land management in the past or inherently low natural soil fertility (Schonou and Herbert, 1989). For instance, in some tropical soils which are acidic and infertile, the performance of trees has been less successful due to the nutrients deficiencies especially P and N. Deficiency of P is common in acid soils because it is fixed in unavailable forms in compounds of Fe and Al (Binkley, 1986).

Most research findings indicate that under conventional management, current rotational lengths, stem wood harvesting and natural nutrient inputs could balance losses associated with harvested products (Schonou and Herbert, 1989). However, it is generally agreed that natural inputs cannot balance losses associated with harvest removals, erosion and leaching. As more intensive harvest practices are used, such as shorter rotations and more complete utilization of biomass, the depletion rate of site nutrient reserves will increase and it is most likely that the present losses will limit future productivity of managed plantations in different sites of the world.

2.2 Fertilization in Forest Plantations

Many tree species in forest plantations in the tropics have evolved in geologically ancient landscape. These species are adapted to withstand long periods of hot and dry weather conditions. Some species such as Eucalyptus are more efficient in conserving nutrients through internal recycling, and many can grow on sites of low fertility (Cromer *et al.*, 1992). Thus on highly weathered soils of low nutrient status, plantations often show a rapid growth and healthy appearance where the climatic conditions and soil physical characteristics are favourable. During, the last two decades, investigations on fertilizer requirements in forest plantation has increased tremendously in an effort to maximize forest yields (Schonou and Herbert, 1989). The impact of these investigations is reflected through the considerable increase in the use of fertilizers when establishing new plantations, and this has now become almost standard practice in some countries such as Brazil, South Africa and New Zealand (Schonou and Herbert, 1989).

2.3 The Status of P in Forest soils

The content of P in forest soils is very variable. A fertile soil may contain in excess of 1000 kg P ha^{-1} in the root-penetrable layers (Tiessen *et al.*, 1994), but only a small portion of the total amount of P is available at any given time to plants. As a result, P deficiencies often develop in forest crops despite a large quantity of total P present in the soil. Total P supply and availability is determined by drainage condition, rooting conditions, P utilization, mineralogical composition of the soil parent material and degree of soil development (Tiessen *et al.*, 1994). Sharma and Kaitha (1996) documented that in acid tropical soils (Ultisols or Oxisols) P is fixed in oxides of Fe and Al and is not readily available to plants. Furthermore, Binkley *et al.* (1992) observed less P especially in soils supporting coniferous stands than in those under hard woods. He further pointed that this is possibly because of the capacity of conifers to survive in low P soils. Additionally, roots of forest trees usually possess mycorrhizal associations that increase the capacity of these trees to utilise less available forms of phosphates in soils (Adams *et al.*, 1989). Sparling *et al.*(1994) reported that in the tropics the total and extractable P were greatest under fertilized land and the annual fluxes through the soil microbial biomass were estimated to be 18-36 kg P ha^{-1}, sufficiently large to make a substantial contribution to plant requirements. Sparling *et al.*(1994) further reported that the current status of the soil several years after the establishment or subsequent reversions is that, there has been no decline in soil and microbial P contents.

2.4 Phosphate Fertilization in Forest Plantations

2.4.1 Scope of phosphate fertilization

Many fertilizer trials established in various parts of the world have demonstrated the overriding importance of P fertilization to the successful establishment of plantations especially in poorly drained soils (Schonou and Herbert, 1989). The results from P fertilizer trials dating back to the 1950's, indicate that benefits from single P application may last to a full rotation and may even carry over to the next rotation (Hunger, 1990). However, the availability of applied P does decline with time and additional responses from reapplication of P within the same or succeeding rotations have been reported (Hunger, 1990). Despite the significant roles of P fertilization in forest plantation, the effect of P fertilization need to be examined in different sites if it has any effect on the availability of other nutrients for instance absorption of Cu, Zn and B (Saur *et al.*, 1995)

2.4.2 Response of plants to P fertilizers

(a) *Effect of P fertilizers on growth*

Increases in the early growth of fast growing tropical hardwood and softwood tree species would be expected if P fertilizers are applied at a time of planting (Cromer *et al.*. 1992). Cromer *et al.* (1992) further reported that application of P fertilizer at time of planting would increase aggregate growth responses and would improve the chance of a positive return on investment on good sites especially at a rate of 100 kg P ha^{-1}. Many studies have reported a strong response in growth rates of softwood and hardwood tree species especially on height and diameter by application of P fertilizers (Schonau *et al.*, 1981; Samwel *et al.*. 1985; Yost *et al*. 1987). Lundberg and Ravnsback (1992) reported a remarkable increase of stem volume by 3-4 m^3 ha^{-1} $year^{-1}$. five years after P fertilization as well as increase in bottom diameter. height and crown diameter and also caused an early canopy closure of the stand. However, Schonau and Herbert (1989) showed that the response of P fertilizers after three years of plantation establishment would become insufficient to stimulate growth. and further concluded that response to P fertilizers has been recorded for many years especially in the tropical and subtropical soils. Most of the results indicated a consistent requirement of P fertilizers in most of the softwood plantations (Cameron *et al.*. 1981).

The contribution to biomass of the whole tree in young stands generally comes mostly from foliage, but at later stages other parts contribute equally or more and it is P fertilizer application which increases the uptake of other nutrients, particularly N and K to enhance a change, although a fraction of P taken up by the trees which was derived from P fertilization decrease and increase in dry matter gradually with time (Wan *et al.*, 1993), and that applied P alone seemed to have significant impact on dry matter partitioning.

(b) *Effect of P fertilizer on foliar nutrient concentration*

Application of P fertilizers has been documented to have an effect on foliar nutrient concentrations and experience had shown that initial fertilizing at plantation establishment with P fertilizers decreased foliar N and K concentrations in the first 9.6 years after planting (Binkley, 1986) although foliar Ca and Mg concentrations increased linearly with the P fertilizer, and there was no significant effect on foliar Mn concentration. Foliar P concentration increased quadratically with the initial P rate, which accounted for 77-86% of the variation in foliar P concentration (Kusum *et al.*, 1993). Most of the explained variation in foliar nutrient concentrations was attributed to the plantation age except for foliar P concentration. In the case of foliar P concentration, 53% of the variation was explained by the initial P rate. It was further reported by Kusum *et al.* (1993) that foliar P concentration of slash pine at age 11.5 years increased quadratically with the initial P rate and linearly with the additional 40 kg P ha^{-1} applied at age 10 years, accounting for 81% of the variation in the foliar P concentration. It was concluded by Kusum *et al.* (1993) that foliar nutrient analysis indicated that P was the major limiting nutrient affecting stand growth in the tropics.

(c) *Phosphate fertilization and litter production in forest stand*

Litter production in forest stands usually affected by the fertilization including P. For instance , the effect of phosphorus fertilization on mass of pine litter accumulated on the forest floor was significantly higher in the P fertilized plots and the fertilization also increased the age of peak litterfall rates (Wienand and Stock, 1995). Wienand and Stock (1995) further reported that in the youngest stand (8 years old) only litterfall contributed to litter accumulation, whereas in the 25-year-old stand, both litterfall and decomposition were significant factors and this was attributed by P fertilization. Other studies reported that P fertilizers enhance dry matter accumulation but lower decomposition. It was further suggested that low decay or decomposition may be ascribed to the lower nitrogen concentration of the fertilized litter which in turn was due to the greater extent of nitrogen retranslocation from needles of the fertilized trees (Wan *et al.*, 1993). The extent of phosphorus retranslocation decreased with phosphorus fertilization which also meant reduced phosphorus use efficiency in the fertilized stands (Wienand and Stock , 1995). Based on the aspects of litter dynamics, it is likely that phosphorus fertilization should be considered when recommending a fertilization regime aimed at maintaining long-term productivity in pine plantations.

2.5 The Concepts of P Availability in the Soil

Phosphorus plays an indispensable role as a universal fuel for all biochemical work in living cells and it is found in sufficient amounts in the earth's crust (Walbridge, 1991; Tiessen *et al.* 1994). Brady and Weil (1996) and Carreira (1997) suggested that the major problem in P uptake from soils by plants is the low solubility of most P compounds which results in very low concentrations of available P in the soil solution. The amount of P in the soil available to plants at any given time may often be as low as 1ppm or less while the average soil solution P concentration is about 0.05 ppm (mg L^{-1}) and varies widely among soils (Tisdale *et al.*, 1993). In most cases the critical soil solution P concentration required by most plants varies from 0.003 to 0.3 mg L^{-1}, and depends on the crop species and level of production. According to Binkley *et al.* (1992), $H_2PO_4^-$ is the most available form to the plants and is replenished by the slow dissolution of the rock minerals (e.g. apatite). He further added that plants and micro-organisms immobilise these ions and a significant amount of the P in soils is converted into organic forms in the soil.

2.5.1 Anomalous behaviour of P in the soil

Phosphorus is the second most important plant nutrient next to N, and occurs in the soil in organic and inorganic forms (Tisdale *et al.*, 1993). Conceptually, the dynamics of P transformation in the soil involves three categories (or pools), namely non-available, potentially available and readily available (Brady and Weil, 1996). Brady and Weil (1996) further reported that this order reflects increased easiness to accessibility or availability for plant uptake. The direction and rate of flow of P between these pools is controlled by many factors, some that are well understood, and others that are not (Stevenson, 1982). It is generally agreed that a better understanding of dynamics of P transformation will provide a strong basis for sound management of soil P, including application of fertilizer P to ensure adequate P availability to plants (Tisdale *et al.*, 1993). Generally plants are unable to absorb P directly from solid compounds or from organic compounds, even when the latter is the soil solution.

2.5.2 Partitioning of P into different pools of availability

Few estimates of available P take into account other pools that might influence available P, notably the organic pool (Guo and Yost, 1998). Soil tests that measure only inorganic P can underestimate potentially available P and the desirability of including other fractions has been advocated (Abbott, 1978). Organic P constitutes a significant portion of total soil

P, ranging from 15 to 80% (Stevenson, 1982), but quite normally 30 to 50% in most soils. Estimating the labile or readily mineralizable organic P may be beneficial in soils with low native inorganic P such as in acid soils with high Fe and Al activity. It may also be useful in tropical soils where much of the P may occur in organic forms and is a major contributor to available P. Although the organic fractions in tropical soils contribute significantly to the P nutrition of crops, this contribution has not been adequately investigated (Sattell and Morris, 1992). The earlier studies by Hedley *et al.* (1982) reported that the P fractionation methods offer a means of relating P in inorganic and organic fractions to the P taken up by crops as well as the P removed by common chemical extractants.

2.5.3 Phosphorus fixation by soil compounds

Sharma and Kaitha (1996) defined P fixation as the process of retention of that portion of P which is not extractable in dilute acids and generally not considered to be readily available to the plants. While it is evident that available N forms (NH_4^+ and NO_3^-) in soils are relatively quite stable and remain available to the plants, $H_2PO_4^-$ react quickly with other ions in soil solution to become less soluble or unavailable to plants.

According to Sharma and Kaitha (1996) reactions of P with Ca, Fe, clays and Al are the most common fixing agents. The concentration of P in the soil solution is primarily a function of the solubility of the fixed forms of P. Because of the low solubility of the fixed forms, the soils become deficient in P. Most of the reactions that are taking place in the soils to make the P unavailable are outlined below.

2.5.3.1 Phosphorus fixation by Fe. Al. and Mn ions

Soluble Fe, Al and Mn are found in strongly acid soils and react with $H_2PO_4^-$ to form insoluble hydroxy-phosphates (Sharma and Kaitha. 1996). The resulting compounds may be precipitated from solution or adsorbed on surfaces of iron and aluminium hydrous oxides or on clay particles. Thus P becomes unavailable to plants more so with increasing acidity and age.

2.5 3.2 Phosphorus fixation by hydrous oxides

Brady and Weil (1996) reported the $H_2PO_4^-$ions react with insoluble hydrous oxides of Fe. Al and Mn such as limonite and geothite and thus becomes unavailable to plants overtime.

2.5.3.3 Fixation by silicate clays

Soil clays are composed of layers of silica and alumina forming silicate sheets in which phosphate ions may directly combine with these clays by replacing a hydroxyl (OH^-) group from Al atom. This may occur at pH values slightly less than 6.5 (Tisdale *et al.*, 1993)

2.5.3.4 Phosphorus fixation in alkaline soils

The mechanisms of phosphate fixation under alkaline conditions are quite different than under acid conditions. Fixation could be in one or both of the following ways: - firstly, precipitation as di-calcium phosphate whereby alkaline soil pH favours the formation of diphosphate ions (HPO_4^{2-}), and also increases the activity of Ca^{2+} which react with HPO_4^{2-} to form insoluble dicalcium phosphate and hydroxy-apatite. Dicalcium or Tricalcium phosphates are relatively unavailable to plants (Tisdale *et al.*, 1993). Secondly, precipitation on surface of solid $CaCO_3$ in which phosphate ions come in direct contact with solid phase calcium carbonate and precipitate.

2.5.4 Factors influencing P availability

2.5.4.1 General concept

Availability of P is a dynamic process, which involves its continuous release into the soil solution as the roots progressively remove it from the systems (Guo and Yost, 1998). According to Carreira *et al.* (1997), forest soils are known to suffer from multiple deficiencies of nutrients particularly those involving P. Brady and Weil (1996) suggested that several factors have been found to influence P availability to plants in various regions, namely soil factors, biological factors and climatic factors.

2.5.4.2 Soil factors

(a) *Soil pH*

Soil pH is one of the factors affecting P availability and utilization. In most soils, P availability is at maximum in the pH range 5.5 to 7.0 and the ion species commonly available to the plants at this range are $H_2PO_4^-$ and HPO_4^{2-} (Lopez-Hernandez *et al.*, 1986). Moreover, Brady and Weil (1996) pointed that the concentration of P found in the soil solution may range from 0.01 to 8 mg l^{-1}, depending on the soil pH. At low pH values P availability is controlled by its reactions with Fe and Al and their hydrous oxides. Above pH 7.0 the ions of Ca and Mg and carbonates of these basic cations in the soil, cause precipitation of any added P and its availability decreases (Schwertmann and Herbillon, 1992).

(b) *Soil organic matter*

Decomposition of soil organic matter forms humic substances and CO_2. Hammond *et al.* (1986) reported that upon hydrolysis, soil organic matter supply some functional groups or anions such as aliphatic acid, carboxylic acid, phenols and oxalates which may lead to the availability of P. Earlier studies by Moshi *et al.* (1994) pointed out that soil organic matter can also block the sites on Fe and Al hydrous oxides and thus reducing phosphate adsorption capacity and thereby releasing P into the soil solution. In most cases organic acids which are naturally present in soils could be adsorbed by ligand exchange onto mineral surfaces and thus compete with phosphate for the adsorption sites.

(c) *Soil texture*

The relative proportion of soil separates is of great importance in determining the soils adsorptive capacity. Phosphorus sorption is a dominant process controlling P availability in ultisols and oxisols with medium and fine textured soils which are the major soils in the humid and sub-humid tropics of Africa (Deckers, 1993).

Many studies have reported that coarse textured soils like sand unlike clay soils, are not good sinks for P because they cannot hold the phosphate ions present in the soil solution (Doumbia *et al.*, 1992) and therefore P sorption is of minor importance in sandy soils that are predominant in the semi-arid tropics of Africa. The increase in P level in coarse textured soils could be due to more availability of P by virtue of their low fixing capacity (Espinosa, 1992).

(d) *Soil aeration*

In most cases soil aeration influences the oxidation state of inorganic compounds. the decomposition of organic matter and release of P and all other complex reactions related to the tree growth (Doumbia *et al.*, 1992; Espinosa. 1992; Deckers. 1993). Therefore soil aeration has a definite effect on the availability and absorption of P as well as other plant nutrients. Soil compaction and structure influence P relationship indirectly through their effects upon soil aeration. Increased compaction may physically impede root penetration resulting in P being positionally unavailable.

(e) *Soil moisture*

Both experimental work and practical observations indicate that P availability to plants is lower in dry than in moist soil (Barber. 1980). Research has shown that an increase in soil moisture tension reduces the uptake of P more rapidly than the uptake of most other nutrient ions (Verma *et al.*. 1987). Many studies have shown that water is one of the most universal solvents and conducting medium for nutrients in plants (Barber. 1980: Bannier *et al.*. 1985: Verma *et al.*, 1987; Bandyopadhyay and Sen. 1987). Phosphate movement in the soil is diffusion limited and the past studies reported by Barber (1980) showed that the percentage by volume of soil that is occupied by soil water determines the average fraction of cross-section area through which the phosphate ions can diffuse. At low level of moisture content, the water molecule structure becomes rigid thus reducing the diffusive flux near the soil particle surfaces and consequently reduces P diffusion. Bandyopadhyay and Sen (1987) and Verma *et al.* (1987) concluded that increasing moisture to optimum level increases P availability of all carriers, particularly with the more water-soluble sources.

2.5.4.2 Biological factors

(a) *Plant factors*

Plants differ in their utilization of P depending on the root system as well as in their ability to grow in soil with low pH status and respond to P inputs. These differences are related to the efficiency of plants to take up and use soil P. Kirk *et al.* (1993) reported that in most cases factors affecting uptake of P include the abilities of the plant to absorb P from low soil solution concentration, to explore a large soil volume; to solubilize soil P through pH changes and finally to release phosphatase enzymes. The availability of soil P can be increased by the organic acid and acid phosphatase exudates released by roots (Delhaize, 1995) and by plant- induced changes in soil pH (Marschner, 1995). Organic acids in root exudates can complex Fe and Al, resulting in release of P bound by Fe and Al oxides (Kirk *et al.* 1993). Hedley *et al.* (1994) reported that most soil P taken up by plants as a result of root induced changes in soil pH and release of P solubility agents was from NaOHPi.

(b) *Soil micro-organisms*

Brady and Weil (1996) pointed out that P held in organic form could be mineralised and immobilised by the mineralization processes that release N and S from soil organic matter, and that soluble P compounds are released when organic residues and humus decompose. The resulting soluble inorganic phosphate ion ($H_2PO_4^-$) is subject to uptake by plants and fixation into insoluble forms by reaction with Fe, Al, Mn and Ca in soils. Generally, organic residues bear low P but when organic matter high in carbon and other nutrients is added to the soil, microbes would increase their activity and immobilise the P in the biomass. The available $H_2PO_4^-$ in the soil solution would temporarily disappear, just as was the case for soluble P, NH_4^+, NO_3^- and SO_4^{2-}.

2.5.4.3 Climatic factors

(a) *Soil temperature*

Temperature may have diverse effects upon P availability. An increase in temperature hastens mineralization of organic P and dissolution of P sources, but simultaneously increase the rate at which released P react with inorganic compounds in the soil. The speed of chemical reactions increases with the rise in temperature. therefore soils of warmer climates are generally much greater fixers of P than soils of more temperate regions (Vitousek, 1984). This could be due to high content of hydrous oxides of Fe and Al in warmer climate soils which controls the availability of P to plants.

(b) *Rainfall*

Rainfall is cited as one of the factors that influence P availability. In areas, which receive acid rain, the soil is expected to be strongly acidic in such a way that Fe and Al ions greatly exceed those of the $H_2PO_4^-$ ions, consequently leading to formation of insoluble phosphates. Hence most of the phosphate become less available to crops (Brady and Weil, 1996).

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Description of the Study Area

Sao Hill Forest Plantations Project is located in Iringa region, in the Southern Highlands of Tanzania ($8^0$18'S to $8^0$33' and $35^0$6'S to $35^0$20'E; 1900 m. a.s.l) (Mhando *et al.*, 1993). The soils of the area are derived from the basement complex igneous rocks. They are considered less fertile than those derived from volcanic ash. The soils are predominantly Kaolinitic with low base saturation, low cation exchange capacity and pH varying from 4.0 to 6.0 (Nykvist, 1976). The mean annual rainfall is about 1000 mm, most of which falls between November and April and corresponding mean air temperature is about 16^0C. The topography is undulating with gentle slopes The native vegetation is generally characterized by grassland with scattered trees and shrubs dominated by species such as *Brachystegia* and *Julbernadia* (Mhando *et al.*, 1993). The Sao Hill Forest Project has an area of 95,000 ha (Ngegba, 1998).

3.2. Stand Types

The Sao Hill Forest Plantation has about 48,000 ha mainly planted with *Pinus patula* which occupies 86% of the total area, about 8% Eucalyptus species and 6% occupied by the rest of the species. These species were established to provide raw materials for large and small industries. There were two separate pure stands of *E. saligna* and *P. patula* and a mixed stand of the two species. Both the pine and mixed stands were established by using nursery-raised seedlings, planted at spacing of 2.5 x 2.5 m. The pure stand of eucalyptus is under a coppice management regime. The stands are on a land with undulating slope ranging from 1 to 10%. Some stand attributes of monoculture and mixed stand are as indicated in Table 1.

Table 1. Stand attributes of the monoculture *P. patula*, *E. saligna* and mixed stands in Sao Hill Forest Plantation, Iringa, Tanzania

Stand type	Stand density (stem/ha)	DBH (cm)	Height (m)	Basal area (m^2ha^{-1})	Volume (m^3ha^{-1})
		Monoculture			
P. patula	1084±241	22.62±1.09	28.02±1.05	24.96±4.81	895±171.0
E.saligna	726±84	13.91±0.36	25.18±1.32	15.76±5.3	177.1±54.6
		Mixed stands			
P.patula	478±105	16.26±0.90	21.14±1.30	6.28±1.19	226.4±43.1
E.saligna	289±109	26.00±1.16	33.07±1.15	11.61±0.92	151.5±12.3

DBH-Diameter at breast height
± -Standard deviation
Source: Maliondo *et al.* (2000)

3.3 Soil Sampling

Soil samples from the top 0 to 20 cm depth were collected from three different stands mentioned in section 3.2. For each site, a pit was dug to characterize the soil at a depth of 0-35 cm, 35-65 cm and 65-110 cm in pine stand, in mixed stand at depth of 0-40 cm, 40-80 cm and 80-100 cm, and at depth of 0-40 cm, 40-75 cm and 75-100 cm in the eucalyptus stand. The difference in sampled soil depths in different stands was based on soil colour changes. Soil core samples were collected from each depth interval for the determination of bulky density and moisture relations. In addition the composite soil samples to a depth of 20 cm were collected at 15 different points within each ustands for a bioassay experiment. The soils were described in the field using the FAO Guidelines for soil Description (FAO, 1990).

3.2.1 Soil Chemical and Physical analysis

Soil analysis included the chemical and physical characteristics of the soil were done as soon as the soil were brought into the laboratory. Among the characteristics analyzed were soil texture by improved Bouyoucus (1992) hydrometer method followed by International Soil Science Classification of diameter classes (Okalebo *et al.*. 1993); soil pH was determined in 1:2.5 ratio of soil:distilled water (Anderson and Ingram. 1993) and in 0.01M $CaCl_2$. 1:1 soil:solution ratio: soil electrical conductivity was determined in 1:2.5 ratio of soil:distilled water by electrical conductivity meter: soil moisture content was determined by weighing the soil tightly covered in the core samples before and after oven-drying at 105^0C to constant weight and then the moisture content (%) was calculated on dry weight basis: bulky density was determined according to Okalebo *et al.* (1993): CEC by ammonium acetate saturation method. Exchangeable cations were extracted by ammonium acetate, and cations in the leachate were determined by atomic absorption spectrophotometer. Available P was determined by Bray I methods while total P and organic P by ignition were determined as described in Anderson and Ingram (1993) followed by colour development and reading by spectrophotometer (Okalebo *et al*, 1993). Soil total N was determined by using the semi-micro Kjeldahl procedure as described in Bremner and Mulvaney (1982). Soil organic carbon was determined by Walkey-Blackwet oxidation using concentrated sulphuric acid and aqueous potassium dichromate and titrating thereafter by using ferous ammonium sulphate (Okalebo *et al*, 1993).

2.2.2 Soil P fractions

Soil P fractions were determined according to Sattel and Morris (1992) and Guo and Yost (1998) procedure.

3.2.3 Phosphate retention studies

The amount of phosphate retained by the soil at different concentrations of phosphate in equilibrating solutions was determined by the procedure outlined by Okalebo *et al.* (1993). Three grams of air-dried soil samples were sieved through a 40-mesh sieve and weighed into 50 ml polyethyne centrifuge tubes. 30 ml of KH_2PO_4 solution containing 0, 10, 20, 30, 40, 50, 60 mg P/ mL in 0.01 M Ca Cl_2 were added to the plastic bottles which were then shaken thoroughly for half an hour twice per day for 6 consecutive days. Three drops of toluene were added into each bottle to arrest microbial activities during equilibration. The soil-phosphate was equilibrated at 25^{0}C. At the end of equilibration time, the soil phosphate suspension were filtered through Whatman No 42 filter papers. The amount of P in the filtrates was determined colorimetrically using the ammonium molybdate ascorbic acid method (Olsen and Sommers, 1982). The amount of sorbed P (Xm) was calculated as the difference between initial and equilibrium solution P (g Pg^{-1} dry soil). The total sorbed P data were fitted to the linear form of the Langmuir isotherms (Eq. 1) as described by Okalebo *et al.* (1993). The data was also fitted to the Feundlich model (Eq. 2).

The linear form of Langmuir model is given as:

$$C/X = C/A + 1/BA, \qquad (1)$$

Where C and X are concentration of P in solution and amount of sorbed P, respectively. The constants A and B are specific for a given soil and are used as indicators of sorption maximum and sorption energy, respectively. Both A and B were obtained by graphic solution from a straight line relationship resulting when C/X is plotted against C.

The Feundlich model is given as:

$$X = a C^{1/b} \qquad (2)$$

and the linear form as

$$\text{Ln } X = \text{Ln } A + (1/b) \text{ Ln } C \qquad (3)$$

Where X and C are as defined above: a and b are constants for a certain soil, giving the sorption capacity when C= 1 mg L^{-1} and degree of non-linearity, respectively.

3.2.4 Bioassay experiment

To determine plant P uptake and available P in the soil, a bioassay experiment was conducted by using pots.

3.2.4 1 Cultural treatments

(i) Fertilizer application and sowing of seeds

Soil samples from the three stands, sieved through <2mm wire-mesh, were treated with triple-superphosphate at 0, 25, 50 and 100 kg P ha^{-1} as indicated in Table 2. The soil samples + fertilizers were thoroughly mixed and then placed in the 2 liter plastic containers (1.8 kg of oven dry weight soil basis). The soils in the plastic containers from three different sites were arranged in an enclosed germination chamber in 3 blocks with 3 replications of 3 pots each. *Eucalyptus saligna* seed was directly sown and raised in the pots.

(ii) Nitrogenous fertilizer application during the growing period

During the growing period, N fertilizer in form of ammonium sulphate was applied at rates of 0, 40 and 80 kg N ha^{-1} in every replication as indicated in Table 2. As the seedlings were very young to withstand a single N application dosage, the fertilizer was split in two. In the first phase N rates of 0, 20 and 40 were applied at the 4th week, while a similar dose for the second phase was applied at the 7th week of growth.

Table 2. Layout for fertilizer treatments of soils from Sao Hill Forest Plantation Iringa, Tanzania

P/N levels	N_0	N_{40}	N_{80}
P_0	N_0 P_0	N_{40} P_0	N_{80} P_0
P_{25}	N_0 P_{25}	N_{40} P_{25}	N_{80} P_{25}
P_{50}	N_0 P_{50}	N_{40} P_{50}	N_{80} P_{50}
P_{100}	N_0 P_{100}	N_{40} P_{100}	N_{80} P_{100}

(iii) Basal fertilizer treatments

A blanket application consisted of the following elements, K at a rate of 13 mg, Mg at 10 mg, Cu at 3 mg, Mn at 8 mg and borax at 1.18 mg per pot, respectively to reduce deficiencies, which may be associated with P and N additions.

(iv) Monitoring of the experiment

Three weeks after planting the seedlings in each pot were thinned to one vigourous seedling. Throughout the experiment every pot was watered daily using distilled water to ensure that the moisture content was at 60% field capacity.

(v) Growth measurements

Plant height was measured after the seedlings were between 2-10 cm height at the end of the third week. Heights from the ground level to the shoot tip were measured to the nearest centimetre at an interval of three weeks: root collar diameters to the nearest millimetre were measured at termination of experiment.

(vi) Harvesting and processing of soil samples

The experiment was monitored for 12 weeks after which the plants were harvested by cutting the plant at the soil surface. washing with distilled water then dried at 70^{0}C to constant weight for 16 hours. and determining the dry matter of the plant shoot components. The roots were also harvested by washing with tap water followed by rinsing with distilled water and similarly dried to determine the root dry matter.

3 2.4.2 Chemical analysis of plants

The dried plant components were grounded to pass through 0.5 mm sieve and then analyzed for foliar P and N concentration. The total P was analyzed based on the procedure of Bremner and Mulvaney (1982) and Okalebo *et al.* (1993). Foliar N was determined by the Kjedahl procedure as described in (Okalebo *et al.*. 1993).

3.2.4.3 Soil analyses after harvesting

A 5-g soil sample was collected from each pot after harvesting. Soils from pots in each treatment were bulked in each replicate and sub-sampled. The samples were air dried and ground to pass a <1mm sieve and then extracted sequentially for P using the procedures described in Guo and Yost (1998). The soil P availability indices were determined by using the following soil test methods: Bray 1 P, Bray 2 P (Anderson and Ingram, 1993); Iron oxide filter paper strips (Shekiffu, 1999); resins (Sattel and Morris, 1992). Untreated soils from different soil depth in each stand were similarly fractionated.

3.3 Data Analysis

Analysis of variance (ANOVA) for a Completely Randomized Block Design (CRBD) was performed on the studied plant height, root collar diameter and soil variables, followed by the Duncan's Multiple Range Test to separate the significant treatments (Zar, 1984; Steel and Torrie, 1984). Correlation and regression analyses were used to establish relationship between plant and soil variables. All the collected data were analyzed using GLM procedure of the Statistical Analysis Software program (SAS Inc. 1991).

CHAPTER FOUR

4. RESULTS

4.2 General Soil Properties

Physical and chemical properties of soils used in the present study are presented in Tables 3a-d. Soil texture was sandy clay for all stands. In general soil bulk density (BD) decreased with depth for the three stands (Table 3a), but surface soil BD was higher in the pine stand (1.5 g cm^{-3}) indicating some compaction. Porosity was also slightly lower in the surface soil of the pine stand than in the other two. Percentage loss on ignition was lower in mixed stand and highest in the eucalyptus stand. Soil moisture content (MC%) was lower in mixed stand.

There was no significant variation in pH between the stands although it was slightly lower under the pine stand. The soils from the three stands are strongly acidic (Table 3b) and generally, $pH_{(H_2O)}$ increased with depth, except for the eucalyptus stand. As expected the pH (H_2O) was higher than $pH_{(CaCl_2)}$ in both stands.

Soil OC, N and CEC (Table 3b) decreased with depth in all three stands with the eucalyptus stand having the highest CEC in the topsoil. Exchangeable acidity decreased with depth, and on average was slightly higher in the pine stand. Exchangeable Al^{3+} also decreased with depth in all stands, but was higher in the pine stand. The dominant exchangeable base in all soils was Ca, which ranged from 1.24 to 1.48 (cmol(+) kg^{-1}) in the top soil. Exchangeable K was low in all stands (< 0.1 cmol(+) kg^{-1}).

Table 3c shows that the average total P was slightly higher in the eucalyptus stand, and decreased with depth for all stands. Total organic P was higher in pine than in other stands and decreased with depth. Available P measured by Bray 1 method was low (<10 ppm) in all stands.

Table 3a. Physical properties of soil from three stands of pine. eucalyptus and eucalyptus-pine mixture in Sao Hill Forest Plantation. Iringa. Tanzania.

	Stand from which soil was collected								
	Pine stand			Eucalyptus-pine stand			Eucalyptus stand		
Depth (cm)	0-35	35-65	65-110	0-40	40-80	80-100	0-40	40-75	75-100
MC%	12.9	17.2	15.2	11.8	11.9	14.0	13.3	17.3	15.1
BD (g/m^3)	1.5	1.3	1.4	1.39	1.25	1.27	1.38	1.36	1.31
Porosity %	43.4	52.8	46.4	47.5	52.8	52.1	47.9	48.7	50.6
LOI (%)	7.3	7.7	7.9	6.27	6.28	6.52	8.7	8.33	8.31
Texture (%)									
Clay	43.0	47.0	43.0	41	43	36	39	47	41
Sand	51.0	46.0	49.0	49	53	61	59	49	51
Silt	6.0	7.0	8.0	10	4	3	2	4	8
TC	SC	SC	SC	SC	SC	SC	SC	SC	SC

SC =Sand Clay
LOI= Loss on Ignition
TC =Textural class

Table 3b. Soil chemical properties in three stands of pine. eucalyptus and eucalyptus-pine mixture in Sao Hill Forest Plantation. Iringa. Tanzania

	Stand from which soil was collected								
	Pine stand			Eucalyptus-pine stand			Eucalyptus stand		
Depth (cm)	0-35	35-65	65-110	0-40	40-80	80-100	0-40	40-75	75-100
Attributes									
pH(H_2O)	4.4	4.5	4.6	4.6	4.7	4.8	4.6	4.4	4.7
pH($CaCl_2$)	4.2	4.4	4.4	4.2	4.5	4.3	4.3	4.2	4.4
%OC	3.7	3.34	1.46	3.82	3.13	2.35	3.83	2.56	2.29
%N	0.04	0.03	0.01	0.04	0.03	0.02	0.04	0.02	0.01
CEC(cmol (+)kg^{-1})	24.8	18.4	20.4	23.6	22.8	21.9	31.6	17.2	20.7
Exchangeable acidity (cmol (+)kg^{-1})	5.95	5.40	4.40	6.01	4.60	2.95	5.50	4.44	3.1
Exch Al (cmol(+)kg^{1})	4.40	3.25	3.0	4.1	2.6	2.6	3.7	2.7	2.4
Exchangeable bases (cmol (+)kg^{-1})									
Ca^{++}	1.48	1.34	1.42	1.42	1.36	1.24	1.42	1.36	1.24
Mg^{+}	0.58	0.11	0.11	0.26	0.16	0.05	0.52	0.11	0.03
Na^{+}	0.21	0.16	0.14	0.29	0.17	0.27	0.29	0.15	0.09
K^{+}	0.10	0.10	0.09	0.23	0.21	0.10	0.13	0.11	0.09
Total soil bases (cmol (+)kg^{-1})	2.37	1.71	1.76	2.2	1.9	1.66	2.36	1.73	1.45
ECEC (cmol (+)kg^{-1})	8.3	7.11	6.16	8.2	6.5	4.61	7.9	6.17	4.55
Al^{3+} saturation %	53.0	45.7	48.7	50.0	40.0	56.4	46.8	43.8	52.7

Table 3c. Distribution of available P. total P and total organic P in soil from three stands of pine, eucalyptus and eucalyptus-pine mixture from Sao Hill Forest Plantation. Iringa. Tanzania

	Stand from which soil was collected								
	Pine stand			Eucalyptus-pine stand			Eucalyptus stand		
Depth (cm)	0-35	35-65	65-110	0-40	40-80	80-100	0-40	40-75	75-100
Attributes									
Available P (mg P kg^{-1})	8.4	7.7	7.2	8.4	10.4	5.4	8.4	4.7	7.5
Total P (mg P kg^{-1})	1132	1146	1046.5	1362	1268	1057	1342	1256	1256
Total Organic P (mg P kg^{-1})	554	547	448	478	311	463	471	311	440

Table 3d. Distribution of different soil P fractions in soils from stands of pine. eucalyptus. eucalyptus-pine mixture from Sao Hill Forest plantation. Iringa. Tanzania

	Stand from which soil was collected								
	Pine stand			Eucalyptus-pine stand			Eucalyptus stand		
Depth(cm)	0-35	35-65	65-110	0-40	40-80	80-100	0-40	40-75	75-100
P fraction				mg P kg^{-1} soil					
Resin P	17.14	13.10	12.12	22.60	12.80	4.20	23.10	14.20	10.57
$NaHCO_3$ -P_i	17.43	12.21	9.22	17.90	12.12	11.73	17.7	11.73	8.25
$NaHCO_3$ P_o	14.11	9.86	5.41	14.10	9.64	9.66	13.8	10.25	4.64
NaOH -P_i	6.42	11.25	11.25	6.89	10.76	11.73	12.1	9.99	12.21
NaOH- P_o	5.31	9.57	9.18	5.32	10.73	25.9	19.4	19.04	18.85
HCl -P_i	0.12	0.21	0.31	0.09	0.04	0.52	0.33	0.28	0.43
Residuae P	13.64	20.30	6.40	16.10	14.30	6.80	20.3	15.10	16.02
Total	**74.17**	**76.5**	**53.89**	**83**	**70.39**	**70.54**	**106.7**	**80.59**	**70.97**

4.3 Estimation of Phosphorus Availability

4.3.1 Chemical extractants of P

4.3.1.1 Iron oxide impregnated filter paper (Iron oxide strip)

The amount of P extracted by iron oxide strip was significantly affected by P fertilizer (Appendix 6) but was not affected (P> 0.05) by fertilizer N or stand type . Among the soil test methods for readily extractable P. iron oxide strips extracted the highest amount of P at all P rates (Table 4a).

4.3.1.2 Resin P

The resin soil test extracted more P than all other extractants. apart from the iron oxide strip method. The amount of P extracted by the resin test was significantly ($P > 0.05$) affected by the P fertilizer rate (Appendix 6).

4.3.1.3 Bray 1 and Bray 2

The two extractants removed similar amounts of available P. and both were significantly affected ($P > 0.05$) by P fertilizer (Table 4a).

Table 4a. Amount of soil P extracted by different methods at varying levels of P fertilizer in soils from Sao Hill forest Plantation. Iringa. Tanzania

	Fertilizer levels kg P ha^{-1}			
	0	25	50	100
Extractant		mg P g^{-1} soil		
Resin	12.69c	19.75b	24.68b	32.39a
	(1.37)	(1.60)	(0.40)	(0.62)
Bray 1	4.99c	5.41c	8.32b	13.36a
	(1.10)	(1.30)	(0.50)	(0.60)
Bray 2	4.69b	5.83b	11.17a	13.41a
	(0.60)	(0.13)	(1.40)	(1.10)
Fe_2O_3 strips	22.62c	24.91cb	28.10b	34.37a
	(1.42)	(1.50)	(1.84)	(1.45)

Means with the same letter within row are not significantly different ($P<0.05$).
Values with parentheses are the standard errors

4.3.2 Phosphorus adsorption

The adsorption isotherms were curvilinear across all the studied soils and fitted a quadratic model in all the soils as indicated in the following equations for control soils only:

Soils from pine stand $Y = -1.1011 + 241.3x - 79.136x^2$ ($r^2 = 0.97$)

Soils from mixed stand $Y = 10.675 + 195.47x - 57.226x^2$ ($r^2 = 0.94$)

Soils from eucalyptus stand $Y = 2.1003 + 190.37x - 51.631x^2$ ($r^2 = 0.98$)

Table 4b shows the sorption isotherm parameters obtained from the linearised Langmuir and Freundlich adsorption models. Based on r^2, the fit of the emperical Freundlich isotherms to the sorption data was better than the Langmuir isotherm for all the soils. In the untreated soils, the Langmuir adsorption maximum was lower in the mixed stand. Average potential buffering capacity was lower in the eucalyptus stand than in the other stands. Bonding energy decreased with increasing fertilizer rate.

Table 4b. Phosphorus sorption parameters as determined by Linearised Langmuir and Freundlich sorption models at varying P levels for three different top soils from three stands in Sao Hill Forest Plantation, Iringa, Tanzania

Soil from	Langmuir constants					Freundlich constants		
	P-rate (kg P ha^{-1})	A*	AB***	B**	r^2	a	b	r^2
	0	1418	717	0.51	0.45	486	0.80	0.87
	25	1332	707	0.53	0.46	470	0.78	0.85
1	50	1346	533	0.39	0.50	374	0.76	0.87
	100	1462	453	0.31	0.49	338	0.80	0.90
	0	947	857	0.91	0.77	442	0.66	0.85
2	25	1011	697	0.67	0.81	400	0.70	0.89
	50	1149	536	0.47	0.56	356	0.72	0.82
	100	1412	422	0.29	0.33	332	0.75	0.78
	0	1314	621	0.47	0.56	417	0.77	0.88
3	25	1504	507	0.33	0.46	373	0.80	0.89
	50	1473	415	0.28	0.63	314	0.81	0.94
	100	2174	339	0.16	0.29	289	0.88	0.92

*A-Adsorption maximum
**B- Bonding energy
***AB-Potential buffering capacity
a and b are constants for the Freundlich model
1- soil from Pine
2- soil from pine-eucalyptus
3 -soil from eucalyptus

4.3.3 Phosphorus fractionation

4.3.3.1 Variation of P fractions with depth in untreated soils

Soil P fractions in untreated soils are presented in Table 2d and show that most of the P was in the following fractions: $NaHCO_3$ P_i. Resins P. $NaHCO_3$ P_o and Residue P. In the pine and mixed stands the first three fractions constituted about 66% of the total P in the top soil. The corresponding figure in the eucalyptus stand was 51%. In general most of the P in $NaHCO_3$ fraction was in the inorganic form. The NaOH fraction was mostly inorganic in the pine stand, while it was mostly organic in the eucalyptus stand. At 80-100 cm depth in the mixed stand. NaOH P_o contributed about 37% of the total P. Residue P was highest in the eucalyptus stand. and accounted for 19% of the total soil P fractions in the topsoil of the three stands.

4.3.3.2 P fractions in P fertilized soils

Only the part of residual P i.e Conc. HCl-P fraction was significantly affected by the soil type ($P > 0.05$) with the mixed stand having more P than the other two stands.

The effect of P fertilizers on the amount of soil P fractions was significant in all the three soil types. Table 4c shows that organic P ($NaHCO_3$ P_o + NaOH P_o) accounted for about 56%, 55%. 53% and 47% of the total P at 0, 25, 50 and 100 kg P ha^{-1} , respectively; implying that the application of P fertilizer slightly decreased the percentage of organic P in the soil, as inorganic P increased (Table 4c).

At 0 kg P ha^{-1} 47% of the total P was extracted as organic P in $NaHCO_3$, decreasing to 36% at 100 kg P ha^{-1}. The next largest fraction was extracted as inorganic P by NaOH, increasing from 20% in the control to 22% at 100 kg P ha^{-1}. The Ca-bound P represented by 1.0M HCl-P contributed about 2.8% varying little with P rate. Residue P (con HCl-P + H_2O_2-P) was 4.7, 3.9, 6.4 and 6.7% at 0, 25, 50 and 100 kg P ha^{-1}, respectively and mostly was in the conc HCl-P. Figure 1 indicates the effect of P fertilizers on soil P fractions, and shows that addition of fertilizer P marginally increased the percentage soil P fractions except for $NaHCO_3$-P_o, which markedly decreased with increasing P rate.

Table 4c. Distribution of soil phosphorus fractions at varying rates of P fertilizers in soils from three stands in Sao Hill Forest Plantation, Iringa, Tanzania

Soil fraction	0	25	50	100
	P fertilizer rate (kg P ha^{-1})			
	mg P kg^{-1} soil			
Resin P	12.69d	17.53c	26.57b	33.78a
	(1.37)	(1.60)	(0.47)	(0.62)
Na_2HCO_3 P_i	8.53c	10.96cb	12.9b	19.09a
	(1.35)	(0.78)	(1.21)	(0.89)
Na_2HCO_3 P_o	61.64c	74.74b	91.13a	91.11a
	(2.33)	(5.31)	(1.72)	(2.38)
NaOH P_i	25.73c	33.06cb	39.21b	57.50a
	(4.07)	(2.35)	(3.70)	(2.70)
NaOH P_o	12.66c	16.28cb	20.15b	28.35a
	(2.06)	(1.16)	(2.16)	(1.33)
HCl-P	3.10c	3.94c	6.72b	8.54a
	(0.09)	(0.30)	(0.31)	(0.46)
Conc HCl-P	5.01c	6.34c	10.70b	13.62a
	(0.16)	(0.46)	(0.46)	(0.74)
H_2O_2-P	1.25c	1.58c	2.71b	3.40a
	(0.04)	(0.12)	(0.15)	(0.19)
Total	**130.61**	**164.43**	**210.09**	**255.39**

Means with the same letters within row are not significantly different at P<0.05.
Values with the parentheses are the standard errors

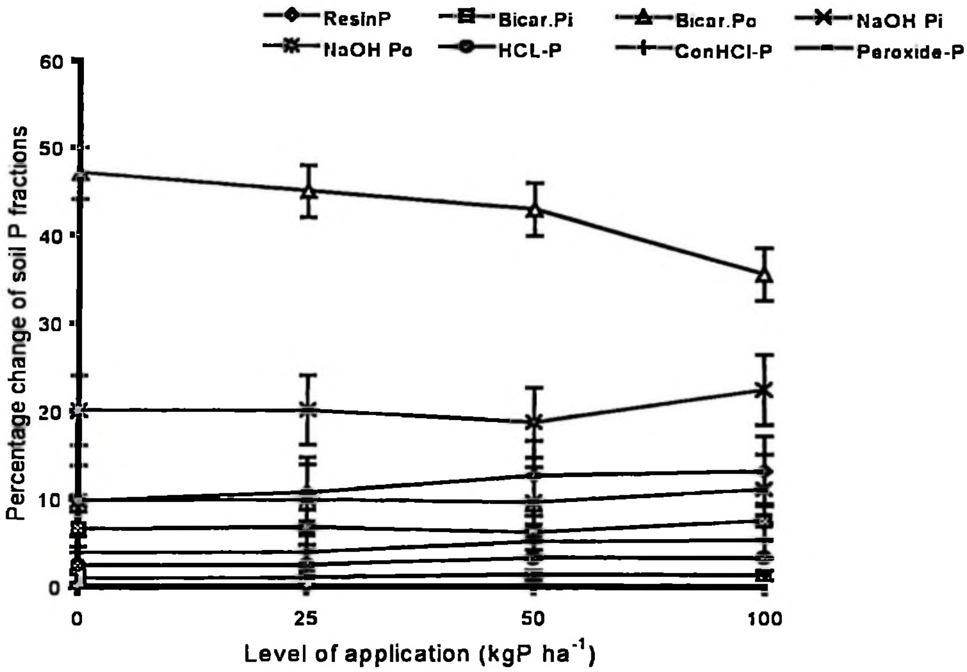

Figure 1. Changes of P fractions as affected by P fertilization in soils from Sao Hill Forest Plantation, Iringa, Tanzania.

4.3.4 Recovery of fertilizer in different soil fractions

The effect of soil type on P recovery by different extractants is given in Figure 2. The percentage of applied P recovered in each fraction were calculated from Table 4c based on the formula presented by Sattel and Morris (1992):

Recovered P=[(F_iP_i-F_iP0)/ Σ_j(F_jP_i-F_iP0)]*100%

Where F_iP_i was P in the *ith* fraction of the P_i treatment, and F_iP0 was P in the *ith* fraction of the P0 (control) treatment. On average, only 7% of the applied P was recovered in the $NaHCO_3$-P_i fraction and 22% in the NaOH-P_i fraction. Resin P accounted for 15-18% of the recovered P.

Most of the added P was recovered as $NaHCO_3$-P_o fraction (Figure 2) accounting for 43% in the pine stand and 40% in the mixed stand but only 25% in the eucalyptus stand. The next largest amount of P was recovered as NaOH-P_i accounting for 27% in the eucalyptus stand, 25% in the pine stand and 17% in the mixed stand.

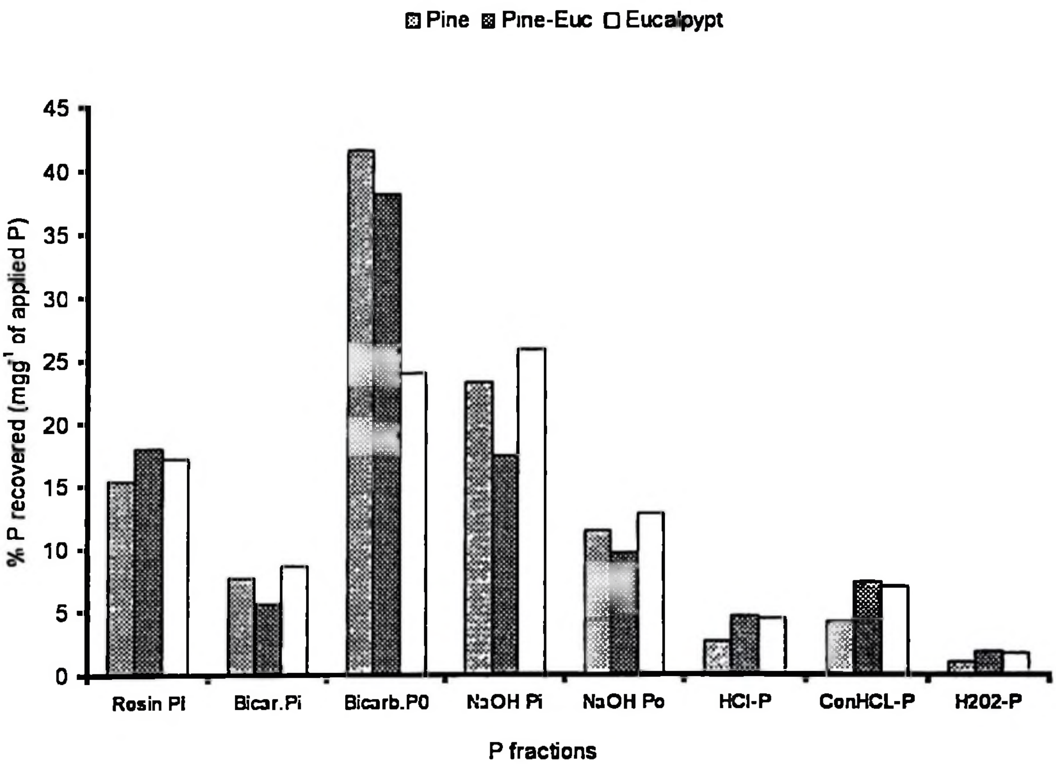

Figure 2. Recovery of inorganic and organic P after P application in three soils in Sao Hill Forest Plantation, Iringa, Tanzania.

4.4 Bioassay Experiment

4.4.1 Effect of fertilizers on *E.saligna* seedlings

4.4.1.1 Morphological assessment

(a) *Plant Height growth*

Application of P fertilizer had a significant ($P<0.05$) effect on height development of *E. saligna* seedlings. Height growth of the seedlings increased linearly with increasing rates of P fertilizer application at each measurement (Figure 3a and Appendix 1&4). In general, height growth of the seedlings was significantly poor in the control. Heights measured at the 3 rd week (H1) and 6 th week (H2) were significantly affected by P fertilizer and blocking. Height growth at the 9th week (H3) of measurement showed a significant interaction between the soil type and P fertilizer (Figure 3b). As indicated in Figure 3b, P requirement in the mixed stand soil peaked at 50 kg P ha^{-1} indicating that, additional P fertilizer would be unnecessary. On the other hand, response to P in the pine and eucalyptus soil was still increasing at 100 kg P ha^{-1} indicating that the soils were highly deficient in P.

The height measured at 12th week (H4) was significantly affected by N and P fertilizers. The means for H4 was 25.4 cm in the control and 30.9 cm at the largest dose of 80 kg N ha^{-1}, indicating that at the time of terminating the experiment N fertilizer had started to elicit a growth response.

(b) *Root collar diameter*

Similar to height, root collar diameter increased with increasing quantity of P fertilizer (Appendix 1&4). However, soil type and application of N fertilizers during the time of growth had no significant ($P > 0.05$) effect on root collar diameter, indicating that available P in these soils was more limiting than N.

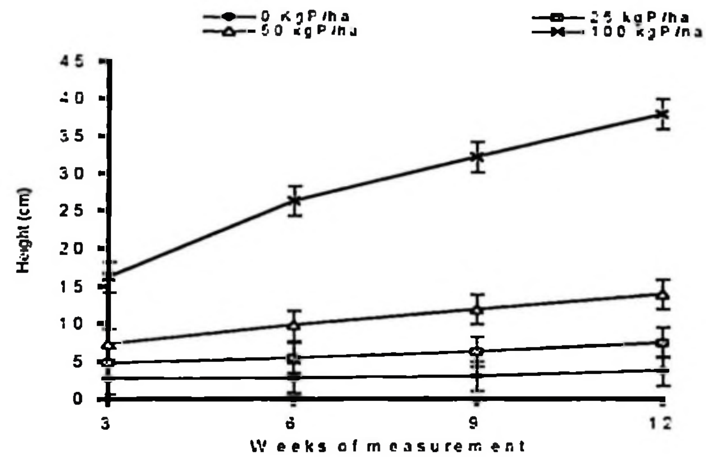

Figure 3a. Effect of P fertilizer on height growth of *E.saligna* seedlings grown in soils from Sao Hill Forest Plantation, Iringa, Tanzania .

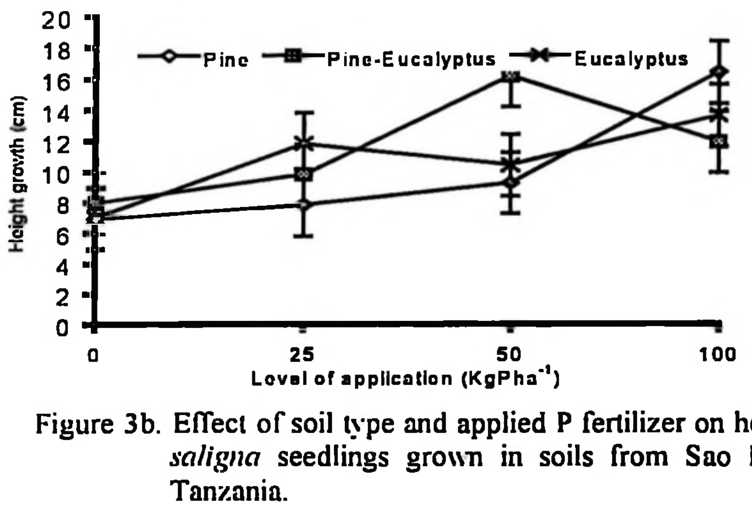

Figure 3b. Effect of soil type and applied P fertilizer on height growth at 9th week of *E. saligna* seedlings grown in soils from Sao Hill Forest Plantation, Iringa, Tanzania.

(c) *Seedling dry weight assessment*

Dry matter production of eucalyptus seedlings was significantly affected ($P<0.05$) by P fertilizer (Figure 4a and Appendix 2). The effect of soil type and N fertilizer was not significant. The P fertilizer effect on the biomass partitioning was highly significant ($P<0.05$) with leaf biomass being higher than all other components while branch biomass was the least (Figure 4a). Figure 4a also shows that leaf and branch biomass peaked at 50 kg P ha^{-1}, while stem and root biomass were still increasing.

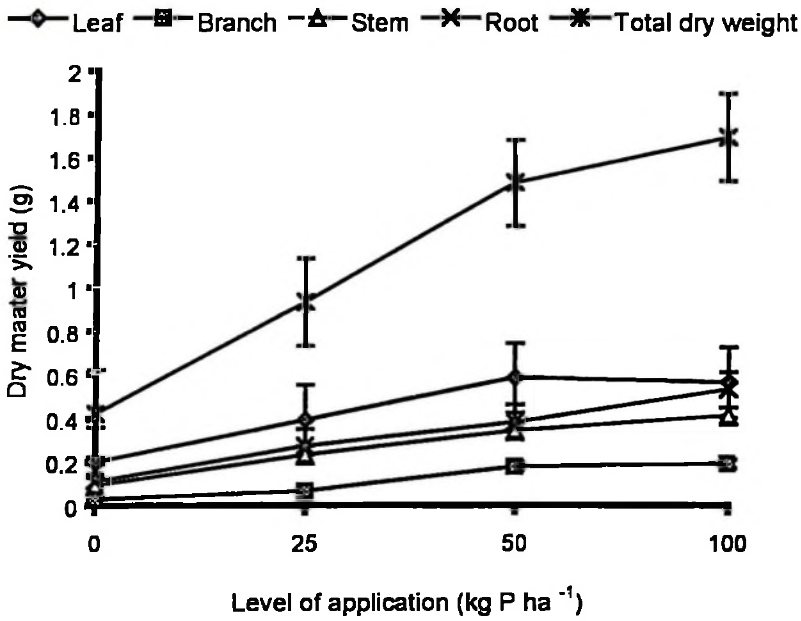

Figure 4a. Effect of P fertilizers on dry matter yield in *E. saligna* seedlings grown in soils from Sao Hill Forest Plantation, Iringa, Tanzania

4.4.1 2 Foliar N and P concentrations

(a) Effect of soil type on foliar P and N concentrations

The effect of stand type was significant ($P<0.05$) for foliar P concentration of *E. saligna* seedlings but not foliar N concentration (Table 5a). The soil from eucalyptus and mixed stands supported seedlings with high foliar P concentration than those grown in the pine soil, indicating that the soil from the pine stand was more P-deficient.

(b) Effect of fertilizers on foliar P and N concentrations

Application of N and P fertilizers on *E. saligna* had significant effect on foliar N and P concentrations indicating a linear response (Table 5b).

Table 5a Effect of soil from different stands in Sao Hill forest Plantation, Iringa, Tanzania on foliar P and N concentrations

	Foliar nutrient concentration (%)	
Soil from	P	N
Pine	0.082b	2.17a
	(0.08)	(0.20)
Mixed stand	0.124a	1.92a
	(0.03)	(0.23)
Eucalyptus	0.125a	2.18a
	(0.04)	(0.12)

Means with the same letter along the column are not significantly different
Values with parentheses are standard errors

Table 5b. Effect of fertilizers on foliar P and N concentrations in *E.saligna* seedlings grown in soils from Sao Hill Forest Plantation, Iringa, Tanzania

	Foliar nutrient concentartion (%)	
Fertilizer type	P	N
$0kgPha^{-1}$	0.076c	2.0ba
	(0.09)	(0.12)
$25kgPha^{-1}$	0.101b	2.5a
	(0.06)	(0.20)
$50kgPha^{-1}$	0.120b	1.6b
	(0.07)	(0.13)
$100kgPha^{-1}$	0.143a	2.3a
	(0.09)	(0.25)
$0kgNha^{-1}$	0.095b	1.8b
	(0.09)	(0.08)
$40kgNha^{-1}$	0.115a	1.9b
	(0.07)	(0.10)
$80kgNha^{-1}$	0.119a	2.6a
	(0.14)	(0.12)

Means with the same letter along the column are not significantly different

4.4.1.3 Correlation between growth variables and foliar N and P concentrations

The correlation between seedlings growth variables and foliar N and P concentrations in *E. saligna* seedlings are shown in Table 5c. and shows that height measured at different intervals and root collar diameter were significantly and positively correlated with foliar P, but not foliar N concentration. Height during the 12[th] week (H4) and root collar diameter were highly correlated with foliar P concentration (r > 0.70).

Table 5c. Correlation between growth variables and foliar P and N concentrations in soils from Sao Hill forest plantation, Iringa, Tanzania

Variable	Foliar P	Foliar N
H1	0.42*	-0.04ns
H2	0.43*	-0.13ns
H3	0.49*	-0.11ns
H4	0.72*	0.11ns
RCD	0.75*	0.11ns
Foliar P	1.00	0.06ns
Foliar N		1.00

H1- height measured at 3[rd] week
H2- height measured at 6[th] week
H3- height measured at 9[th] week
H4- height measured at 12[th] week.
*Significant at 5%(P<0.05)
ns not significant at 5% (P>0.05)

4.4.1.4 Plant P uptake by *E. saligna*

Plant P uptake determined at the end of the experiment was significantly (P<0.05) affected by P fertilization (Appendix 5). Figure 4b shows that P uptake in the 100 kg P ha^{-1} was more than 13 fold higher over the control. The partitioning of P content within the seedling components is shown in Figure 4b. The applied P fertilizer had a significant effect on leaf, stem and branch and root P content with the highest P content being in the leaves.

There was a significant interaction between P fertilizer and soil type on P uptake of *E.saligna* seedlings as indicated in Figure 4c. The soils from pine-eucalyptus mixture showed that P uptake peaked and levelled off at 50 kg P ha^{-1} while in the other two soils P uptake was still increasing.

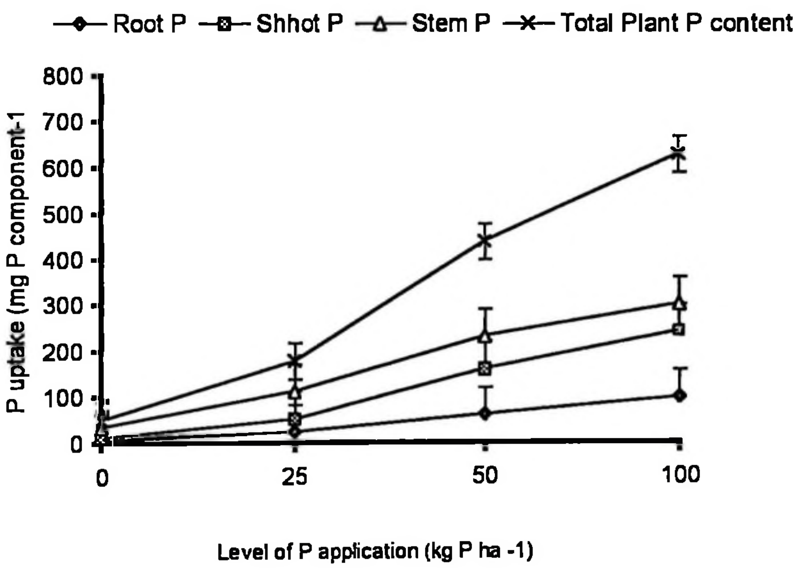

Figure 4b. Effect of P fertilizers on P uptake in *E.saligna* seedlings grown in soils from Sao Hill Forest Plantation, Iringa, Tanzania

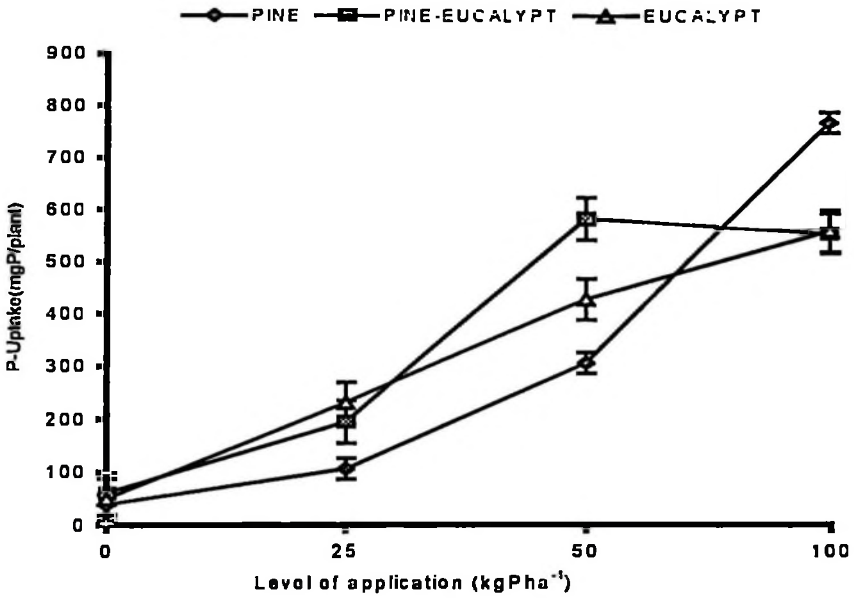

Figure 4c. Effect of P fertilizers and soil type interaction on P uptake in *E. saligna* seedlings in soils from Sao Hill Forest Plantation. Iringa. Tanzania

4.5 Relationship between P Availability Indices and Plant P Uptake

Correlation coefficients between P availability indices and plant P uptake are presented in Table 5d. which shows that plant P was significantly and highly correlated with Bray- 2-P (r=0.70). resin (r=0.64) and Bray-1-P (r=0.63. The iron oxide filter strip method in this study extracted more P in the soil but the correlation with plant P uptake was small (r = 0.59) compared with other soil test methods. The correlations among the soil test methods were also significant (Table 5d).

Table 5d. Simple correlations between P availability indices and plant P uptake in soils from Sao Hill Forest plantation. Iringa. Tanzania

P availability index	Resin	Bray 1	Bray 2	Fe_2O_3 strips	P uptake
Resin	1.0	0.61*	0.69*	0.63*	0.64*
Bray 1		1.0	0.72*	0.65*	0.63*
Bray 2			1.0*	0.62*	0.70*
Iron Oxide strips				1.0	0.59*
P uptake					1.0

* Significant at 5% (P=0.0001)

4.6 Correlation between Soil Test Methods, P Uptake and P Fractions

The correlation coefficients between soil P fractions and P extracted by the soil test methods and with P uptake are presented in Table 5e. Most of the extraction methods correlated well with at least three of the soil fractions (Table 5e). The Resin P fraction was strongly correlated with the other three extractants (r ≥ 0.64) and P uptake (r=0.72). The Resin P soil test method was also significantly correlated with all P fraction. except Con HCl-P. Bray 1 P was strongly correlated with organic and inorganic P extracted by NaOH and $NaHCO_3$. but not $NaHCO_3$-P_o. Except for Conc. HCl. Bray 2 was significantly. but weakly correlated with most of the fractions. The amount of P extracted by Fe_2O_3 strip was significantly correlated with $NaHCO_3$-P_o and H_2O_2-P. Plant P uptake was signficantly correlated with all fractions except conc HCl-P. The correlation of P uptake with 1M HCl and part of sparingly available P (H_2O_2-P) were particularly high (r ≥ 0.66).

Table 5e. Simple correlation coefficients relating P extracted by soil P test methods. P uptake and P fractions in Sao Hill forest soils. Iringa. Tanzania

	Resin-P	$NaHCO_3$-P_i	$NaHCO_3$-P_o	NaOH-P_i	NaOH-P_o	1MHCl-P	ConHCl-P	H_2O_2-P
Resin P	1.0	0.60*	0.53*	0.61*	0.66*	0.55*	0.26+	0.51*
Bray 1P	0.64*	0.65*	0.16+	0.65*	0.66*	0.60*	0.17+	0.35*
Bray 2P	0.73*	0.51*	0.47*	0.51*	0.54*	0.52*	0.18+	0.37*
F_2O_3	0.65*	0.19+	0.63*	0.19+	0.27+	0.14+	0.06+	0.47*
P uptake	0.72*	0.50*	0.52*	0.50*	0.53*	0.66*	0.24+	0.67*

*Significant at 5%
+ not significant at 5%

CHAPTER FIVE

5. DISCUSSION

5.1 Effect of Stand on General Soil Properties

Soil samples were collected from pure stands of pine, eucalyptus and a mixed stand of the two species. Soil bulk density (BD) decreased with depth in all stands (Table 3a) possibly due to logging or site preparation operations which caused compaction of the topsoil especially when heavy machineries were used in the study area. Migunga and Dykstra (1996) reported that the mean surface BD at a depth of 0-15cm in the forest plantation ranged from 0.87 to 1.16 g cm^{-3} which is less than the values (1.25-1.5 g cm^{-3}) reported in this study. Other studies by Miller *et al.* (1996) and Hajabbasi *et al.* (1997) reported a 20% increase in soil bulk density during harvesting and subsequent cultivation. Chijicke (1980) reported higher bulk density in topsoil of pine stand than in natural forest stands. Studies by Kadeba and Aduayi (1985) in a pine stand showed a significant increase in the bulk density of the topsoils. The increase in soil bulk density and hardness following logging reduced exchangeable cations, available P, organic matter and total N (Dowlings *et al*, 1995).

Soil porosity in this study was lower in the surface soil of the pine stand. According to Hartmann *et al.* (1994) harvesting operations usually reduced soil porosity as a result of increasing bulk density. Garg and Jain (1996) reported a value of 40 to 48% porosity in fuelwood plantation, while Cao *et al.* (1991) reported about 67.5% in bamboo stands. Many authors concluded that soil porosity increases as succession proceeds especially in the forest soils and may have a serious effect on the availability of some soil nutrients (Cao *et al.*. 1991; Hartmann . 1994)

Soil pH values indicated that the soils from all stands are acidic and this could be attributed to the high concentration of Al compounds in the soil which continuously release hydrogen ions into the soil solution. However. mean soil pH$_{(H_2O)}$ was slightly higher in mixed and eucalyptus stand than in the pine stand and this is in accordance with Pritchett (1979) who reported that the foliage of broad-leaved tree species usually have higher base content than conifers. Canopy leaching of bases by rainfall might have contributed to the lower acidity of soil under eucalyptus and mixed stands. Several studies have shown that soil pH is related to the availability of the exchangeable bases. CEC. P and N (Pritchett. 1979; Jasbir *et al.*, 1995; Balagopalan and Jose. 1995). In this study the pine soil had higher exchangeable acidity and exchangeable Al than the other stands due to pine litter.

Loss on ignition was higher in the eucalyptus coppice stand perhaps reflecting residual effects of the logging slash after harvesting. As expected soil OC, N and CEC (Table 2b) were generally higher in the topsoil from all the stands. The values of %OC in the top soil reported in this study averaged 3.8%. Ukpong (1995) reported a range of 2.8 to 6.8% OC in tropical soils. which decreased with depth, and that small values of OC occurred in soils with low species diversity or crown cover. Decreases in %N and CEC with depth are related to the decreasing organic matter with depth. Soil %N was below 0.10% indicating that the soils were highly N deficient in all stands (Landon, 1991; Msanya *et al.*,1996). However, total N is a poor indicator of available N (Landon, 1991). In the pine and mixed stand soil CEC was within the range of 15 to 25 (cmol(+)kg^{-1}) considered by Landon (1991) as medium, while in the eucalyptus it would be ranked as high. The exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) are very low. Soil ECEC was low and Al^{3+} saturation accounted for 49%. This could be attributed to the low pH and high rate of leaching of bases as reflected by higher concentration of hydrogen and Al on the soil exchange sites (Landon, 1991).

5.2 Soil P Status

5.2.1 Total soil P

The eucalyptus and mixed stand had higher amounts of soil total P than the pine stand and this is in accordance with Binkley (1986) who reported that eucalyptus stands contribute more to the total P than pines stands although the responsible mechanism is still unknown. The values of total P presented in this study ranged from 1047 to 1342 mg P g^{-1} soil in all the studied soils and these values are within the range of 357 to 4700 mg P kg^{-1} soil reported by Brady and Weil (1996) for various soils of the world. The slight decrease in total P with increasing depth in all stands could been explained by the higher organic P in the surface soils. In this study the total organic P constituted about 32 to 47% and was highest in the pine stand. According to Stevenson (1982) the organic P in the tropical soils range form 15 to 80%. Mueller *et al.* (1995) reported that organic P had a high long range variability which is related to the clay content of the soils and further concluded that the magnitudes of total P, organic P and extractable P are highly related to the soil humus.

5.2.2 Estimation of P availability

5.2.2.1 Chemical extractants

The amount of extractable soil P by all extractants was significantly affected by applied P, indicating that applied P increased the labile P in the soils while at the same time reducing soil P fixing capacity since the soil was saturated with added P.

In this study the iron-impregnated filter paper extracted more soil P followed by the Resin method. Less P was extracted by other soil extraction methods. This is in agreement with the results of Shekiffu (1999) and Guo and Yost (1999) who reported the high capacity of iron strips to extract soil P. The efficiency of Resin P method is supported by Sattel and Morris (1992) who reported that resin P method can extract 2 to 3 times more P than Bray 2 and Bray 1, respectively. Considering the shaking period adopted in this study for resin extraction, it is thought that kinetic exchange of P by resin would be from soil solution as well as from readily exchangeable P from mineral surfaces (Shekiffu, 1999). This may then imply that the resin extractable P is a composite value that should reflect both quantity and intensity factors involved in P uptake (Sattel and Morris, 1992). Resin P was strongly correlated with P uptake indicating that it was estimating a plant available pool. In the acid soils of Sao Hill Forest Plantation, Bray 2 method is recommended for routine analysis for estimating P availability since it was correlated with plant P uptake (r=0.70).

5.2.2 Phosphorus adsorption

In the untreated soils, adsorption maximum was the highest in the pine soil and lowest in the mixed stand. Nieminen and Jarva (1996) have reported adsorption maximum in 0-30cm layer in peat soils to be 673 mg P g^{-1} which is lower than the value observed in this study. Osodeke *et al.* (1993) reported a range of 125 to 750 mg P g^{-1} in tropical acid soils from Rubber belt in Nigeria. Also a range of 324 to 507 mgPg^{-1} was reported by Bachik and Boert (1981) in tropical soils.

Although the Feundlich model had been reported to be entirely empirical. it produced better fit to the adsorption data (r^2 ≥80) than the Langmuir model. In most cases. the Langmuir adsorption maximum increased with fertilizer rate. while potential buffer capacity and the affinity constant decreased with P fertilize application. The decrease in affinity constant with P addition in the study soils may have been caused by the low concentration of native labile P. since there is relationship between bonding energy and the fraction of the total sites available for P adsorption (Agbenin and Tiessen. 1994). Most of the studies have reported bonding energy or affinity constant <1 as reported in this study. Carreira *et al.* (1997) reported a bonding energy of 0.11 in the control and 0.15 in an acid mist treated soils.

The potential buffering capacity was slightly lower in eucalyptus stand than in other two stands. The decrease in potential buffering capacity with P fertilizers is contrary to the report by Humpreys and Pritchett (1972) that the potential buffering capacity is considered as inherent property of the soil and hence changes should not be expected. The soil from eucalyptus stand had the lowest buffer capacity compared to other stands. Sattel and Morris (1992) reported a potential buffering capacity ranging from 838 to 12384 mg P g^{-1} soil in Alfisols with pH above 4. Thus the value of potential buffering capacity reported in this study are within the range reported in other studies.

5.2.3 Soil P fractionation

(a) phosphorus fractions in unfertilised soils

In the present study, the total P obtained during the routine analysis was more than 1000 mg P kg^{-1} while the total P from the fractionation process was less than 110 mg P kg^{-1}. This is because the fractionation procedure used in this study did not consider the sonicate P which was regarded as P that, by being located within small stable aggregates, was physically inaccessible. According to Sattel and Morris (1992) the occluded P or sonicate P may constitutes about 11% of the total P. Guo and Yost (1998) also reported very low values of P fractions in highly weathered soils as compared to the total P.

With respect to soil P fractionation, the readily available P (Resin P + $NaHCO_3$ P_i), ranged from 38 to 49% and was lowest in the eucalyptus stand; this range is higher than 17 to 30% reported by Guo and Yost (1998). Sattel and Morris (1992) reported that the readily available P in untreated soils constitute about 9% which is much lower than the values reported in this study.

Reversible P on exchange surfaces ($NaHCO_3$ P_o + $NaOHP_i$ + NaOH P_o) was 32 to 43% which is similar to the values of 32 to 48% reported by Guo and Yost (1998) and 49% reported by Sattel and Morris (1992).

According to Guo and Yost (1998), the sparingly available P, represented by residue P for highly weathered soils of Hawaii constituted about 28 to 49%. Sattel and Morris reported a value of 26% which is close to average of 19% of total P for the three soils in this study.

Ca-bound P (1M HCl) constituted about 0.2% which is almost negligible compared to the value of 5.3% reported by Sattel and Morris (1992).

(b) P fractions in P treated soils

The distribution of most of soil P fraction in P fertilized top soils, was not significantly affected by stand type, reflecting the similar physico-chemical properties of the soil in the three stands as the stands were located on the same landscape position. Sattel and Morris (1992) showed significant difference in soil P fractions in Sri Lankan Alfisols collected from various landscape positions.

The resin method extracted a mean of 12% although the absolute amount extracted increased with P rate. This suggests that the readily available P to plant roots is about 12%. If readily available P includes Resin P + $NaHCO_3$ P_i (Guo and Yost, 1998), then it accounts for 18% of the total P

Analysis of the control soils revealed that the readily available P (Resin P + $NaHCO_3$ P_i) was about 44% which decreased to 16% after the plant growth which suggests that the reduction was caused by plant uptake. The reversibly available P was increased from 38 to 77% perhaps as a result of mineralization and mobilization on to the readily exchangeable sites, and this suggests that most of the added P was in the reversibly exchange sites. The sparingly available P (Residue P) decreased from 19% to 4.8% mostly due to the dissolution.

Organic P measured as $NaHCO_3$ P_o averaged 43% of the total P. This represents the potentially mineralizable P, it is considered to be part of the reversibly available P (Guo and Yost, 1998). The total reversibly available P constituted a mean of 76% of the total P which is much higher than 47% reported by Sattel and Morris (1992). Stevenson (1982) reported that since organic P constitutes a significant proportion of total soil P from 15 to 80%, there is a need of incorporating organic P in estimating potentially available P. Other studies reported that organic P accounted for about 55% of the total P, and in most cases correlated with the changes in organic matter (Hedley *et al.*, 1982). This suggests that based on the tree growth and the magnitude of the organic P fraction, the readily soluble organic fractions could be the most important P form for long term forest productivity.

Addition of P fertilizers significantly affected the soil P fraction whereby mean organic P% in this study varied from 57% at 0 kg P ha^{-1} to 47% at 100 kg P ha^{-1} . Similar results were reported by other authors including Sattel and Moris (1992) who reported about 44% at 0 kg P ha^{-1} decreasing with increasing P rate. A value of 43% was reported by Sharpley *et al* (1987). This study supports earlier findings that increases in P fertilizer decreases the percentage of organic P in the soil, while at the same time increasing the inorganic fraction. Zaharah *et al.* (1985) found that most of the soil organic P fractions, in absolute terms, increased with increasing P rate which supports the findings of this study. Earlier studies by Mishra and Khanna (1982) showed that Fe-P was the most dominant source of P in the labile pool, but after fertilization Al-P was a dominant form.

5.2.4 Recovery of fertilizer in different soil fractions

Most of the added P fertilizer was recovered as organic $NaHCO_3$ and $NaOHP_i$ and resin P_i fractions Hedley *et al.* (1982) reported that presence of microbial biomass may have a significant effect on the recovery of the organic soil P fraction. Sattel and Morris (1992) also reported that the soil organic matter may form complex compounds with added P which in turn increases the organic P pool. The study by Sattel and Morris (1992) noted that on average 54% of the added P was recovered in the $NaHCO_3$-P_i fraction and about 27% was in the NaOH-P_i. The values reported in this study are smaller than those found in the literature, perhaps because the soil used in this study is more acidic.

5.2.5. Bioassay experiment

5 2.5.1 Growth response of *E. saligna* seedlings to fertilizer application and soil source

The strong response to P fertilizer indicates that the three soils were strongly deficient in P. Increasing P supply enhanced growth in height and root collar diameter of *E. saligna* seedlings in soils from three stands from Sao Hill forest plantation. These results concurs with Cromer *et al.* (1992) who reported that application of P fertilizers at the time of planting or sowing would improve growth response and hence positive returns are expected on investment on such sites. Yost *et al.* (1987) reported that growth rates of *E. saligna*, especially on height and diameter, were improved by the application of P fertilizers. However, they further suggested that the response to P fertilizers after three years of plantation establishment would become insufficient to stimulate further growth. The results of this study show that the growth response was mainly linear for soils from two stands indicating that the optimum level had not been reached. Cameron *et al* (1981) concluded that responses of pine species to P fertilizers has been recorded for many years especially in the tropical and subtropical soils and most of the results indicated a consistent requirement of P fertilizers in most of the softwood plantations. Several workers have shown a strong relationship between P fertilizers and growth rate of Eucalyptus (Schonau *et al.*, 1981; Samwel *et al.*, 1985; Yost *et al.* 1987; Schonau and Herbert, 1989).

The current study also revealed that there was no growth response to N fertilizer at seedlings stage of *E. saligna*. These results agree with the results of Cameron *et al* (1981) who reported that the application of N as ammonium nitrate in N deficient soils reduced seedlings health and survival dramatically in the nursery. Similarly, O'connell (1994) found no response to increased rate of N and concluded that high concentration of N in the soil could have contributed to such poor response. In this study ammonium sulphate was used as a source of N and the results showed low N response. Thus, it is suggested that organic N mineralization was sufficient to supply the N requirements of *E. saligna* seedlings during the growth period as foliar N levels were 1.8% in the control.

The poor growth response of *E. saligna* seedlings to N fertilizers is supported by only few authors: most workers have reported a high response to N fertilizers (Samwel *et al.* 1985; Troeng and Ackzell, 1988; Hogberg, 1989). Some of these studies indicated that without N addition, plants usually failed to utilize other nutrients such as P and K. It is generally agreed that no single element, such as P alone, influences growth, and in general growth increment whether of diameter or height is usually elicited by a combination of nutrients such as NP, NK, NP or NPK (Schonau *et al.*, 1981; Yost *et al.* 1987; Schonau and

Herbert. 1989). In this study other nutrients, except N and P, were applied to all treatments, and thus their deficiency was not expected.

This study indicated that total plant dry matter and dry matter partitioning were significantly affected by applied P fertilizer but not N fertilizers or the soil source. In contrast, Yost *et al.* (1987) reported that P fertilizers did not increase plant dry weight. In contrast, Driessche (1988) noted that N fertilizers were more effective on dry weight production due to the gains in diameter and height, caused by N fertilizers. The strong response to P fertilization in this study supports the postulate that soil P is deficient in the acidic soils of Sao Hill Forest Project. Furthermore, this study shows that changes in total dry matter among treatments were primarily due to changes in the production of new foliage supporting more photosynthate production and partitioning within the plants but the increased aboveground biomass production was at the expense of root biomass. The slight shift in allocation of dry matter from belowground to aboveground components is in agreement with the earlier reports by Mead *et al.* (1984) on *Pinus radiata*.

The lack of response in total dry weights and dry weight partitioning to N fertilizer in this study is contrary to many studies (Mead, 1984; Madgwick *et al.*, 1988; Beets *et al.*, 1988) which reported that changes in plant dry matter was caused by the effect of N fertilizer and not P fertilizers.

5.2.5.2 Foliar P status and P uptake in *E. saligna* seedlings

The present study indicated that seedlings grown in the soil from eucalyptus and mixed stands had sufficient foliar P concentration suggesting that P deficiency should not be a serious problem in these stands. In contrast, the foliar P concentration of seedlings raised in pine stand was within deficiency range of 0.06 to 0.09% in *E. saligna* as reported by Dreschsel and Zech (1991), indicating that the pine stand was highly deficient in P. The high foliar P concentration of *E. saligna* for the soil from eucalyptus stand is similar to the study by Samwel *et al.* (1985) who reported that *E. saligna* can utilize the relatively insoluble phosphates in the soils and increase P availability. Application of N and P fertilizers significantly increased N and P foliar concentration of *E. saligna* seedlings confirming that foliar nutrients can be used to predict soil nutrient deficiencies. In this study, the foliar N concentration supports the suggestion that N was not deficient as foliar N was within the critical level of 1.2 to 2.1% which indicates high fertility as reported by Dreschsel and Zech (1991). Application of P fertilizer increased the foliar P concentration to the required level while without P fertilizer the deficiency was noticeable. Generally, foliar analysis has certain advantages as diagnostic technique whereby it gives better relationships between foliar nutrient concentration and relative growth response (Cromer *et al.* 1992).

The P uptake in *E. saligna* seedlings was significantly increased by the application of P fertilizers. The increased P uptake with P addition, imply that P was a limiting factor in this study. This is in agreement with the previous study by Tiessen *et al.* (1994) which noted that any increase in P fertilizer induce more plant P uptake in P deficient soils.

Most of the P taken by the plants in this study was translocated to the aboveground biomass and more P was in the leaves and stems, and the least in the roots. It is likely that increased mycorrhizal association enhanced P uptake despite the low root weight.

In this study there was an interaction between soil and applied P fertilizers on stem and branch P concentration and P uptake. Phosphorus uptake and stem and branch P concentration in mixed stand peaked at 50 kg P ha^{-1}, perhaps a reflection of the low adsorptive capacity of the soil from mixed stand.

5.3 Correlation between Soil Extractants, P fraction and P Uptake

As reported in this study, iron oxide strips extract more P in the soil but the correlation with P uptake was lower than with the Bray-1-P and 2-P methods. The lower correlation of iron oxide strip method in this study is contrary to the report by Kumar *et al* (1992) that the iron oxide strip method gave better relationship with plant uptake. It is likely, that this method extracted proportions of soil inorganic P, which might not be accessible to plant, roots in the short-term, but reflect long term P availability.

Although the amount of P extracted by the different methods varied, they were significantly correlated with P fractions and P uptake. In most cases the correlation between soil P extraction methods, P uptake and P fractions depend on which form of P is dominant in the soil (Stevenson, 1982). The highly significant and positive correlation between P extracted by the four soil test methods, P uptake and their correlated fractions may well provide further evidence in support of the assumption that these are perhaps the dominant forms of inorganic P in most of the soils (Hedley *et al.*, 1982).

CHAPTER SIX

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Phosphorus deficiency was more severe than N deficiencies in the studied soils from Sao Hill. Iron oxide filter strip method extracted more P in the soils than the other tests used in this study, but was weakly correlated with P uptake than other extraction methods. Resin P and Bray-2-P as measures of P availability were superior to all other soil tests for predicting P uptake by the test plant. The results support the idea that extractants, which remove small amounts of P, are more useful in evaluating short-term P availability in forest soils.

In this study, the adsorption maximum, maximum buffering capacity and bonding energy were affected by soil from different stands indicating that stand type play a role in phosphate isotherm characteristics. Moreover, addition of P fertilizers decreased the bonding energy and maximum buffering capacity but adsorption maximum was little affected by P fertilization.

The distribution of the soil P fractions was not different since the soil from all the three stands was situated on the same location. Most of the soil P was in reversibly available pool and was increased by P application. The high P recoveries of fertilizers in organic fractions is evidence that organic P contributed significantly to soil P availability.

The present study further indicated that the soil from different stands had significantly affected foliar P concentration of *E.saligna* seedlings with the soil from eucalyptus stand and the mixed stand having higher P availability than the pine stand that was P deficient.

The study also shows that P fertilization improved soil fertility and subsequent growth, dry matter production and P uptake in *E. saligna* seedlings on the soils collected from pine, pine-eucalyptus and eucalyptus stands indicating that all soil were P deficient, but varying extent. For example, a P rate of 50 kg ha^{-1} appeared sufficient for the pine-eucalyptus soil but not for other two soils.

Likewise, application of N fertilizers to *E.saligna* seedlings significantly increased to N foliar concentration indicating that the level foliar nutrients can be used to predict soil nutrient status.

6.2 Recommendations

- The results from this study support earlier findings that P is severely deficient in Sao Hill and thus application of P but not N fertilizer at the time of planting is recommended, preferably at rates between 50 to 100 kg ha^{-1}.
- Bray-2 method as a measure of P availability was superior to all other soil tests for predicting P uptake by the test plant. Therefore this method is recommended for routine analysis of acid soils of Sao Hill Forest Plantations.
- More research is recommended on the effect of N fertilizers on the growth of plantation tree species.
- More research is recommended in different soil P extractants especially for those, which not used in this study.
- Further studies on soil P fractions should be recommended in other locations of the forest plantation for the more appropriate conclusion

- In order to minimize frequent P loses and subsequent deficiencies, harvesting residues should not be removed from the sites or burnt since upon decomposition they contribute significantly to soil organic P and hence P availability resulting from organic matter mineralization.

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APPENDICES

Appendix 1. The influence of P fertilizers on height and root collar diameter of *E.saligna* seedlings grown in soils from Sao Hill Forest Project, Iringa, Tanzania.

Applied P levels kgPha^{-1}	Seedlings height (cm)				Root collar diameter (mm)
	H3	H6	H9	H12	
0	2.67c	4.78c	7.28c	16.21d	0.16d
25	2.74b	5.48cb	9.78b	26.32c	0.25c
50	3.02b	6.29b	11.93ba	32.27b	0.31b
100	3.70a	7.54a	13.96a	38.64a	0.37a

Means with the same letters in the same column are not significantly different at P<0.05.
H3- height measured at 3rd week
H6- height measured at 6th week
H9- height measured at 9th week
H12- height measured at 12th week.

Appendix 2. The influence of P fertilizers on dry weight components of *E.saligna* seedlings grown in soils from Sao Hill forest Project, Iringa, Tanzania

Applied P levels kgPha^{-1}	Dry weights (mg)			
	Roots	Stem	Branch	Leaf
0	0.111d	0.086c	0.026b	0.199c
25	0.247c	0.227b	0.069b	0.389b
50	0.379b	0.336a	0.1769a	0.562a
100	0.53a	0.4070a	0.189a	0.583a

Appendix 3. The influences of P fertilizers on components P contents of *E.saligna* seedlings grown in soils from Sao Hill Forest Project, Iringa, Tanzania

Applied P levels kg P ha^{-1}	P content (mg P plant^{-1})			
	Roots	Stem and Branch	Leaf	Total P uptake
0	0.00502c	0.098c	0.034d	48.54d
25	0.022c	0.048c	0.1079c	177.28c
50	0.058b	0.155b	0.225b	438.44b
100	0.097a	0.237a	0.297a	0.627.7a

Means with the same letter within the rows are not significantly different

Appendix 4. Probability for F ratio of the effect soil type, block and N and P fertilizers on growth and dry matter yield of *E. saligna* seedlings grown in soils from Sao Hill Forest Plantation, Iringa, Tanzania.

Source of varaiation	H1	H2	H3	H4	RCD	DRT	DLF	DBR	DST	TDW
Soil	0.3918	0.8352	0.2312	0.0599	0.1733	0.7434	0.9507	0.1053	0.5431	0.6360
Block	0.0422	0.0181	0.0312	0.9398	0.3892	0.3918	0.0392	0.9684	0.4149	0.2250
N	0.7781	0.6183	0.3865	0.0130	0.5126	0.9219	0.5115	0.0618	0.3872	0.5484
P	0.0009	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
P*N	0.2882	0.0721	0.0225	0.4122	0.4345	0.3331	0.1029	0.0021	0.0768	0.2364
Soil*P	0.1935	0.2448	0.0001	0.7065	0.9877	0.3899	0.2543	0.0024	0.1126	0.5324

H1, H2, H3 and H4 as defined in appendix 1
DRT- root dry weight
DLF- leaves dry weight
DBR- branch dry weight
DST- stem dry weight

Appendix 5. Probability for F ratio of the effect soil type, block and N and P fertilizers on P uptake of *E. saligna* seedlings grown in soils from Sao Hill Forest Plantation, Iringa, Tanzania.

Source of variation	DRTP	DLFP	DSTBRP	P uptake
Soil	0.891	0.851	0.3204	0.6053
Block	0.326	0.0563	0.1810	0.1500
N	0.5597	0.0842	0.0801	0.0894
P	0.0001	0.0001	0.0001	0.0001
P*N	0.3905	0.0817	0.0588	0.0630
Soil*P	0.1167	0.1008	0.0136	0.0273

DRTP- root P
DLFP- leaf P
DSTP- stem and branch P

Appendix 6. Probability for F ratio of the effect soil type, N and P fertilizers on different extractants in soils from Sao Hill forest Plantation, Iringa, Tanzania

Source of variation	Resin P	Bray 1 P	Bray 2 P	Fe_2O_3 strips	P uptake
Soil	0.5599	0.0459	0.0979	0.0915	0.4856
N	0.7195	0.9639	0.9566	0.1370	0.4231
P	0.0001	0.0001	0.0001	0.0026	0.0001

Appendix 7. Probability for F ratio of the effect soil type, N and P fertilizers on soil P fractions

Source of variation	Resin-P	$NaHCO_3$-P_i	$NaHCO_3$-P_o	NaOH-P_i	NaOH-P_o	1HCl-P	ConHCl-P	H_2O_2-P
Soil	0.5599	0.5922	0.2612	0.5712	0.6019	0.4519	0.0240	0.2325
N	0.7195	0.7912	0.4700	0.8289	0.9103	0.3193	0.4566	0.9841
P	0.0001	0.0001	0.0036	0.0001	0.0001	0.0001	0.2367	0.0101