

**ROCK PHOSPHATE RECAPITALIZATION: A P FERTILIZER FOR
MATURE OIL PALM (*Elaeis guineensis* Jacq.) IN THE SEMI-
DECIDUOUS FOREST ZONE IN GHANA**

KNUST



BY

Isaac Danso

January, 2009

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KUMASI-GHANA

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DECIDUOUS FOREST ZONE IN GHANA**

**A Thesis submitted to the Department of Crop and Soil Sciences,
Kwame Nkrumah University of Science and Technology
in partial fulfillment of the requirement for the award of the degree of**

Master of Philosophy

in

Soil Fertility/Plant Nutrition

By

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B.Sc. (Agric.) KNUST, Kumasi

January, 2009

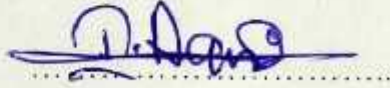
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DECLARATION

I declare that I have personally under the supervision, undertaken the study herein submitted.
This thesis has never been presented at any occasion at any University for the award of a degree.

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We declare that we have supervised the student in undertaking the study submitted herein and confirm that the student has our permission to present it for assessment.

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DEDICATION

Dedicated to my wife Matilda and Children – Kwarteng and Afriyie. On many occasions, you were left at home alone without my protection, as I had to be elsewhere for this work. Thank you for the sacrifices made. May God bless you.

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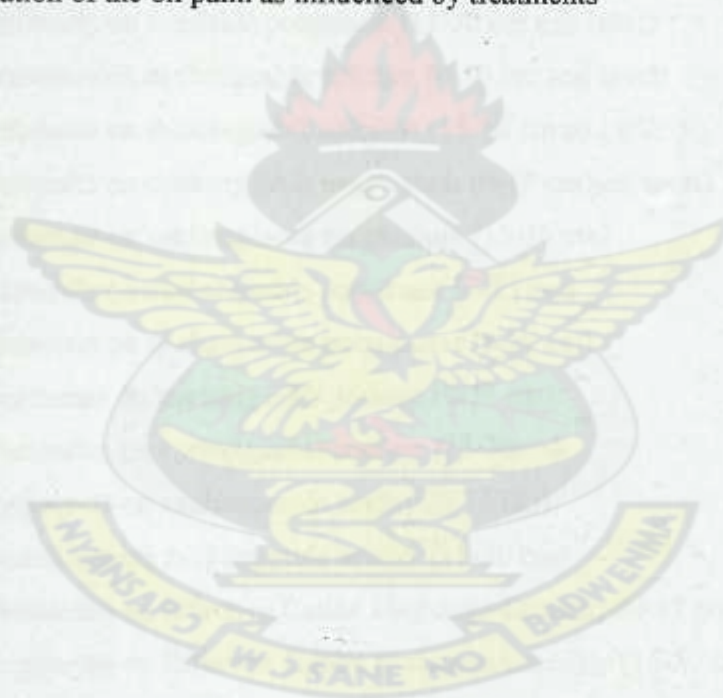
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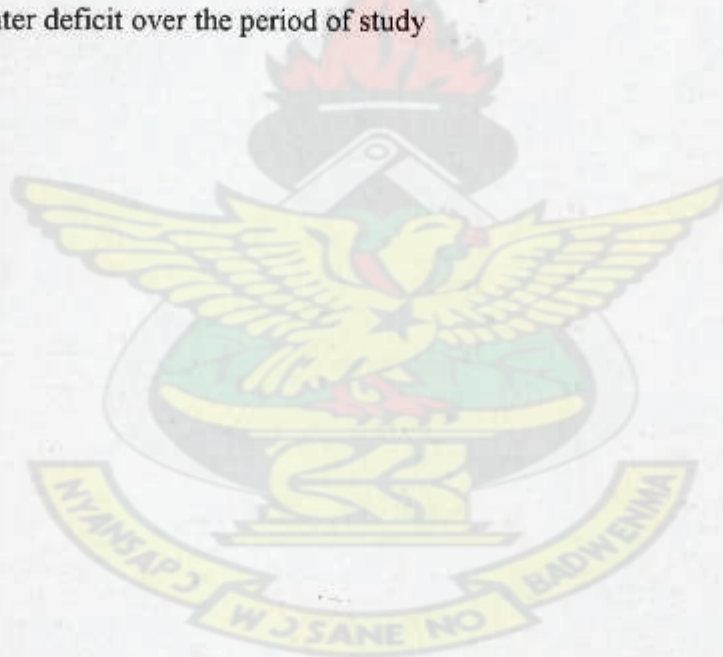
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ABSTRACT

The study focused on direct application of phosphate rock (PR) as an alternative source of phosphorus (P) to the use of superphosphate (triple superphosphate) for mature oil palm (*Elaeis guineensis* Jacq.) in the semi-deciduous forest zone of Ghana. The objectives of the study were to assess the fertilization effect of phosphate rock (PR) on the growth, development and yield of oil palm. The experiment also aimed at studying the influence of PR on soil microbial activity under oil palm as well as the influence of PR on soil nutrient changes. The economic benefit of using PR under oil palm was examined.

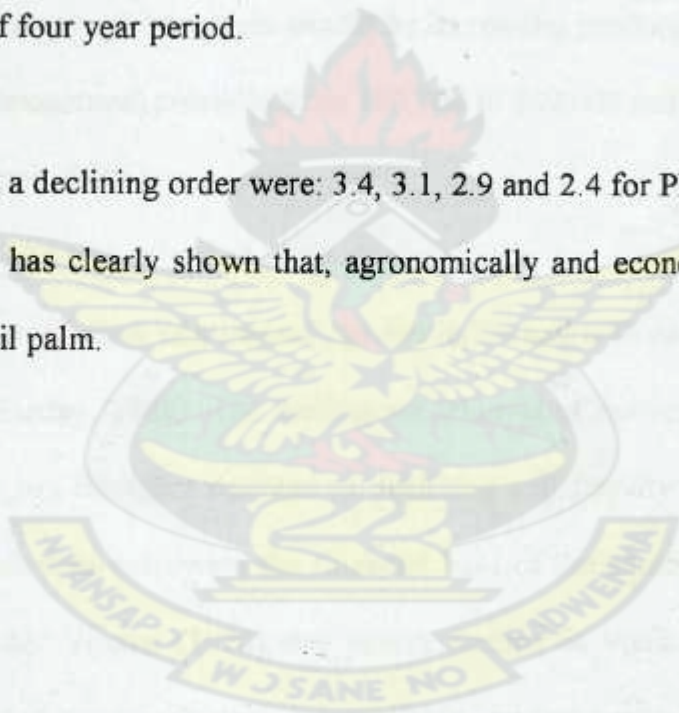
A field experiment was conducted between 2003 to 2007 at the Oil Palm Research Institute (OPRI), Kusi in the semi-deciduous forest zone of Ghana. The study was carried out on the soils of Nzema series classified as Ferric Acrisols (FAO) and Typic Hapludult (USDA). The oil palm trees selected were 8 year old tenera (DXP ex OPRI). Each plot measured 17.6 m x 17.6 m and had 6 palms. There were four treatments, consisting of: 1). TSP - OPRI fertilizer recommendation - 222 kg of AS + 222 kg of TSP + 296 kg of MOP / ha / yr (control); 2). PR1 - PR 715 kg + 222 kg of AS + 296 kg of MOP / ha - Yr 1. PR 358 kg + 222 kg of AS + 296 kg of MOP / ha - Yr 2. PR 358 kg + 222 kg of AS + 296 kg of MOP / ha - Yr 3; 3). PR2 - PR 1428 kg + 222 kg of AS + 296 kg of MOP / ha applied once in every 5 years; 4). PR3 - PR 142.85 kg / ha + 222 kg AS / ha + 296 kg of MOP / ha applied twice in every 5 years.

Chemical analysis of the soil indicated that application of treatments influenced the soil chemical properties to a varying extent. Soil pH ranged from extremely acidic (3.73) to acidic (5.43). Available K was as high as 125 mg/kg with available P recording 9.55 mg/kg which was slightly

below the medium range of available P for oil palm production. The use of PR improved soil chemical properties especially increasing exchangeable Ca, Mg, K and ECEC.

The results showed that treatment PR2 was effective and gave the highest oil palm fresh fruit bunch yield of 62.8 t/ha while the TSP was the least effective with a production of 53.7 t/ha. Development, growth and yield response of P fertilization by palms followed the trend: PR2 > PR3 > PR1 > TSP. This trend could be attributed to sustainable supply of P to palm trees by PR than TSP. Microbial C, N and P were higher at the 4th year of study than during the 1st year of study. PR2 recorded the highest microbial C and N values, with PR3 holding more available phosphorus at the end of four year period.

The cost benefit ratio in a declining order were: 3.4, 3.1, 2.9 and 2.4 for PR3, PR2, PR1 and TSP respectively. The study has clearly shown that, agronomically and economically it is sound to use PR under matured oil palm.



CHAPTER ONE

1.0 INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) cultivation in Ghana is dominated by small scale farmers who occupy about 70% of estimated total area of 145,500 hectares under the crop, with the remaining 30% of the oil palm production area being accounted for by development estates (GOPDA, 1990).

The President's Special Initiative (PSI) on oil palm has been found to be a new pillar of growth which will help Ghana to expand its current citadel by increasing production of oil palm through improved agronomic management practices from 100,000 to 240,000 hectares within the next 10 years (PSI-Oil Palm Report, 2003).

Oil palm is a perennial crop which continuously grows in the soil with economic lifespan falling between 25-30 years (Hartley, 1988). The continuous removal of nutrients through Fresh Fruit Bunches (FFB) harvest has therefore resulted in declining soil fertility. This causes a serious decrease in yield per unit area narrowing the financial base of the small-scale oil palm farmer. This agrees with Van der Vossen (1970) that severe decline in yield of oil palm in Ghana resulted from depletion of organic matter and available nutrients particularly phosphorus (P) through uptake, leaching and P-fixation.

Phosphorus deficiency in ~~crops~~ constitutes the second most important soil fertility problem throughout the world (Sanchez and Salinas 1981). Wells and Allen (1985) have all indicated that phosphorus is the second most limiting element in alfisols, oxisols and ultisols of the tropics.

Phosphorus deficiency in such soils is often worsened by a high capacity to fix P in different forms, making it less available to crops (Quang *et al.*, 1996). It is no wonder that improvement and maintenance of soil fertility, through application of P fertilizers for example, have become a key factor in effort to sustain crop production including oil palm.

The efficiency and sustainability of added P to weathered and highly acidic soils for tree nutrition partially depend on the types of material used. The most common fertilizers are superphosphates in the tropics, and phosphate rocks (PRs) in the Far East (Hartley, 1988).

The high cost of soluble phosphate fertilizer, such as single superphosphate (SSP) or triple superphosphate (TSP), has generated considerable interest in the utilization of PR (Nnadi and Haque, 1988). Apart from being a cheaper source per kg of P, P from PR is slowly available and very effective under acidic conditions ($\text{pH} < 4$) to perennials like oil palm, hence there may be less loss of P through sorption. According to Yeates (1993), PRs can be more efficient than water soluble phosphate (WSP) fertilizers in terms of recovery of phosphates by plants, even for short term crops in soils where soluble P is readily leached, as in sandy soils and possibly for long term crops like oil palm. In addition, Sale and Mokwunye (1993) noted that PR is now considered as Ca fertilizer playing a vital role in raising the pH of the soil medium.

Oil palm has become so expensive to grow in Ghana that, P deficiency should not be allowed to limit yield. However, this goal is far from reality by oil palm farmers in Ghana, since the use of superphosphates are beyond their reach. This necessitates research to investigate alternative material that can be used as P fertilizer source.

Working on the hypothesis that direct application of PR sustainably favours effective growth, development and yield of oil palm under conditions of high acidity and low levels of available phosphorus, the objectives of this study were to:

- i. determine PR fertilization effect on the yield and development of oil palm within four years period.
- ii. study the influence of PR on soil nutrient changes under oil palm.
- iii. study the influence of PR on microbial biomass C, N and P under oil palm.
- iv. evaluate PR economic benefit in oil palm cultivation in semi-deciduous forest zone of Ghana.



CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 THE PHYSIOLOGY OF GROWTH AND DEVELOPMENT OF OIL PALM

Oil palm productivity is influenced by the total dry matter production of each palm. Dry matter production is highly dependent on the photosynthetic rate of the palm (Dolmat, 1996).

2.1.1 The role of leaves in dry matter accumulation of plants

Various concepts are used to characterise the role of leaves in dry matter accumulation in relation to growth analysis of plants.

- i. **Leaf Area (LA):** Nutrient deficiency reduces growth in general and leaf area in particular. Corley and Mok (1972) showed that N and K increases LA. Restriction in water supply was demonstrated to affect leaf expansion (Boyers, 1970; Acevedo *et al.*, 1971).
- ii. **Leaf Area Index (LAI):** Leaf area index varies according to leaf orientation (Pearce *et al.*, 1967). Kriedemann and Smart (1971) demonstrated that vertically oriented foliage makes good use of both diffuse and direct sunlight and can therefore achieve greater LAI. Corley and Mok (1972) showed that high N levels give rise to faster LAI development. Similar effects have been observed with irrigation.
- iii. **Leaf Area Duration (LAD):** This measures the persistence of the leaf canopy. If leaf area index is plotted against time, the area under the curve is a measure of the duration of

the leaves. Corley (1973) has suggested that provided leaves are not removed by pruning, their life depends in part on the intensity of light reaching them through the canopy.

- v. **Crop Growth Rate (CGR):** Growth rates can be compared at different times in the season for different treatments. Crop growth rate is affected by a range of factors including temperature, radiation levels, water, nutrient supply and the type and age of the plant (Corley and Mok, 1972). These factors affect the size and efficiency of the leaf canopy and hence the ability of the crop to convert solar energy into useful growth.

2.1.2 Oil palm dry matter accumulation and distribution

The dry matter produced is used for both vegetative and reproductive growth. In the oil palm, vegetative growth assumes priority over the reproductive growth (Hartley, 1988). Thus the requirements of vegetative growth must necessarily be satisfied before dry matter is diverted into fruit production.

For economic production of the oil palm therefore, it is imperative that management practices which would enhance the availability of such factors influencing vegetative growth and development of the oil palm are adopted.

2.2 FACTORS INFLUENCING GROWTH AND DEVELOPMENT OF OIL PALM

Many factors affect the rate of photosynthesis of the palm. These are predominantly climatic, edaphic and agronomic practices.

2.2.1 Climatic factors

Oil palm is now grown in most tropical countries where climate is favourable. Differences in climatic factors affect productivity. Rainfall, temperature and light intensity are the main climatic factors which affect the growth and development of the oil palm.

2.2.1.1 Rainfall and water balance

The annual rainfall distribution relative to potential evapotranspiration with the buffering effect of soil water reserves defines the water available for the plants (Surre, 1968). In the sub-region of West Africa, the seasonality of rainfall and the long drought which lasts 2 to 4 months in a year result in huge water deficits. The amount and distribution of rainfall and therefore soil moisture availability influence leaf production. There is evidence that within West Africa, annual leaf production is low in areas with rainfall of 1250 mm and below.

Desmarest (1967) noted that stem growth was fastest in plantations sited where water supply was satisfactory against slowest stem growth on plantations sited where there was limited water supply. Quency and de Taffin (1981) observed that the insufficient water supply in West Africa mainly affects the sex ratio of the palms and thus determines the number of bunches produced.

Olivin (1968) found good correlation between the mean annual water deficit and the average production level. Surre (1968) and IRHO (1969) also found direct relationships between the magnitude of water deficit estimates and bunch yield. Desmarest (1967) demonstrated that, in the Cote d'Ivoire yields of fresh fruit bunches could be raised by irrigation from 7.5 to 26 t/ha. This was collaborated by the work of Ochs and Vander Wegen (1969) who reported yield increases of 13t/ha by applying irrigation in the Cote d'Ivoire. Rees (1989) thought irrigation may not be

economically feasible considering the large areas involved in oil palm cultivation and the cost of the necessary equipment coupled with their maintenance costs. Therefore husbandry practices that conserve soil moisture might be the best option.

2.2.1.2 Temperature

There are indications that temperatures below 20 °C for any extended period are generally deleterious to oil palm. Hartley (1988) found temperature differences to be the most distinguishing climatic factor between Yangambi, Zaire and the Far East. Yangambi had minimum of between 19.3 and 20.3 °C while the Far East had a minimum of 23 °C. The former has a lower yield than the latter.

2.2.1.3 Light use for oil palm growth and development

Another environmental factor which has a large influence on the photosynthetic output of the oil palm tree is light. Shading adult palm reduces the production of female inflorescence. Sparnaaij (1960) demonstrated this by pruning the leaves of adjacent palms to increase the production of female inflorescence.

In Ghana and other West African countries, with marked seasonal differences in hours of sunshine, the differentiation of female inflorescence as shown by the sex ratio at flowering two years later, is much higher during the months with many hours of sunshine than during the months with few hours (Broekmans, 1957).

2.2.2 Soil factors affecting the growth, development and yield of the oil palm

Besides the inherent fertility of the soil, mineral nutrient absorption by the oil palm is highly dependent on such soil physical properties as aeration and moisture status (Hartley, 1988).

2.2.2.1 Soil physical factors

According to Hartley (1988) for optimum oil palm production, the soil must be deep and loamy with a well developed structure. Soil should have a loose friable consistency and must be without impervious layers in the top 1.5 meters. Drainage must be good to ensure aeration. The soil must, however, be capable of holding ample moisture for the oil palm (Olivin, 1968; Ochs and Olivin, 1969). Growth and development of the oil palm is impaired on soils with high water table especially the young plants which cannot tolerate stagnant water. Heavy, badly drained soils and coarse sandy soils which are easily depleted of moisture are not suitable. Dolmat *et al.* (1982) and Rasmussen (1981) showed that peat soils could be suitable provided they are well drained and deep enough to provide sufficient anchorage for the root system of the oil palm.

2.2.2.2 Mineral nutrient requirement

The oil palm needs large quantities of nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg) which are important for both vegetative and yield production. These nutrient requirements of the oil palm vary with age (Foster and Chang, 1977), variety (Poon *et al.*, 1970), level of production and management practices which among others include planting density and cover management (Hartley, 1988).

Yield potential of the environment also dictates nutrient requirement. Therefore when yield is restricted by such factors as inadequate rainfall, shallow soil depth and poor drainage, nutrient

requirement is also depressed (Foster *et al.*, 1985). The natural nutrient supply of any soil is only of limited capacity. Extra supplies in the form of fertilizers are practically always needed. These are applied from the very first year of planting in the field.

Soil analysis indicates the quantity of nutrient at the disposal of the palm. Soil nutrient supply capacity indices are shown in Table 1. Fertilizer is applied to bring the soil nutrient supply capacity from low to the high level as and when necessary.

Table 1. Soil nutrient supply capacity indices

Nutrient	High	Medium	Low
Total N (%)	> 0.2	0.1 – 0.2	< 0.1
Available P (mg/kg)	> 20	10 – 20	< 10
Available K (mg/kg)	> 100	50 – 100	< 50

Source: Hartley (1988).

Foliar analysis identifies and quantifies the deficiency of individual nutrients so that fertilizer adjustments can be calculated. The leaf nutrient concentrations are indicative of the nutrient status of the palm trees. Critical leaf nutrient levels are presented in Table 2. Below or above these sufficiency levels, fertilizer use needs to be increased or withheld.

Table 2. Critical levels of oil palm leaf nutrient

Areas	N	P	K	Ca	Mg	Sources
	—————%					
Ivory cost and Benin	2.50	0.15	1.00	0.60	0.24	IRHO (1960)
Nigeria	2.50	0.16	1.00	-	0.28	WAIFOR (1956)
Malaysia	2.40	0.15	1.00	0.60	0.24	Ollagnier (1973)

2.3 SOIL NUTRIENT STATUS OF AREAS CLIMATICALLY ZONED FOR OIL PALM PRODUCTION IN GHANA

An estimated 10 – 15 percent of the 23.9 million hectares of potentially arable land in Ghana comprises highly weathered soils of low base status (Owusu-Bennoah *et al.*, 2000). These soils are in the humid rainforest agro-ecological zone of the country where oil palm is grown. The major constraint to increased food-crop production in this area is the inherently low soil fertility status (Owusu-Bennoah *et al.*, 1997). Their buffering capacity as well as cation exchange capacity is also low since their pre-dominant clay mineral is kaolinitic with sesquioxides (Mongia and Bandyopadhyay 1993).

Phosphorus is one of the most limiting nutrients for sustained crop production in these acidic soils noted for tree crops cultivation like oil palm. Low solution P concentration and a high P sorption capacity are the two common problems in these acid soils (Owusu-Bennoah *et al.*, 2000).

Current studies clearly show poor soil fertility status of most soils under oil palm production. At Bogoso in the Western region, Tetteh and Dedzoe (2004) and Tetteh *et al.* (2002) evaluated the soil fertility levels of some benchmark soils under oil palm, cocoa and maize. According to the authors, soil fertility levels of most of the soils are very low. Most of the soils are acidic ($\text{pH} < 5.0$), low in available P and exchangeable cations. Similar studies at Bawjiase in the central region revealed similar results regarding soil fertility status (Dedzoe *et al.*, 2004). This also agrees with the studies by Asamoah and Nuerthey (2005) that areas climatically suitable for optimal oil palm production in Ghana have limitations including poor drainage, hazards of erosion, high acidity and low nutrients.

Soils in oil palm growing areas have predominantly light textured surface horizons, with heavier textured soils being confined to valley bottoms. There are also extensive areas of shallow, concretionary and rocky soils, which have low water holding capacities and low soil nutrients limiting its suitability for agriculture.

According to Van der Vossen (1969), using values of mean annual water deficit delineated oil palm growing areas into climatic zones for economical oil palm cultivation (Fig. 2.1). Soils in these areas are developed from pre-Cambrian rocks, mainly phyllites and granites but in the extreme south-west there is an area of tertiary sandstones contiguous with that of the Ivory Coast. Satisfactory and sustained yields have been obtained on typic hapludox intergrades over phyllites, but on oxisols derived from tertiary sands, the maintenance of satisfactory yields has presented problems (Van der Vossen, 1970).

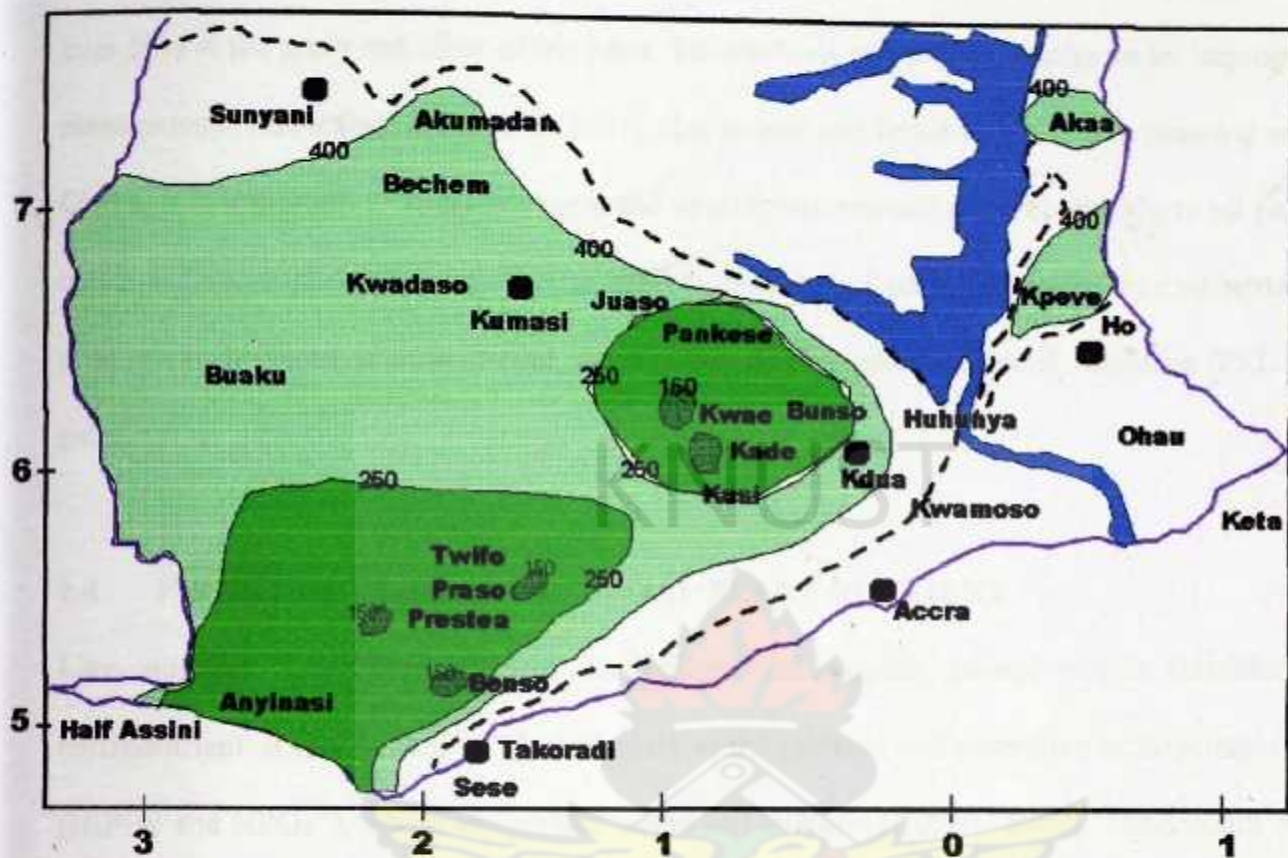


Fig. 2.1: Areas climatically suitable for Oil palm production in the Forest Zone of Ghana.

LEGEND

- REGIONAL CAPITAL
- LIMIT OF THE FOREST ZONE
- VOLTA LAKE
- 160 MEAN ANNUAL WATER DEFICIT (mm) OPTIMUM AREA FOR OIL PALM PRODUCTION
- 250 MEAN ANNUAL WATER DEFICIT (mm) FAVOURABLE AREA FOR OIL PALM PRODUCTION
- 400 MEAN ANNUAL WATER DEFICIT (mm) SUITABLE AREA FOR OIL PALM PRODUCTION

SOURCE: VAN DER VOSSEN (1969)

The importance of fertilization was underlined by Rhodes (1995) in oil palm growing areas. He stated that total crop uptake over 10 years were 428,700 t N, 73,100 t P and 414,900 t K with over 50% in the grain and other edible parts. Thus serious soil mining results under improper soil management. According to Ibrahim (2001), due to low soil fertility in oil palm growing areas in Ghana, it is important to apply adequate and appropriate amount of NPK and Mg to oil palm for better and sustainable production. The need to fertilize oil palm for increased and sustainable production in Ghana is now critical, considering the President's Special Initiative (PSI) on oil palm.

KNUST

2.4 PHOSPHORUS AS AN ESSENTIAL PLANT NUTRIENT

Like, nitrogen, potassium, calcium, magnesium and sulphur, phosphorus is classified as a macronutrient. It is absorbed by plants largely as the primary and secondary orthophosphate ions (H_2PO_4^- and HPO_4^{2-}), which are present in the soil solution (Robert, 2002). The amount of each form present depends largely on the solution pH. At pH 7.2 there are approximately equal amounts of H_2PO_4^- and HPO_4^{2-} . Below this pH, H_2PO_4^- is the main form. The secondary orthophosphate ion (HPO_4^{2-}) becomes most important at pH values above 7.2. Plant uptake of HPO_4^{2-} is much slower than it is with H_2PO_4^- . Some soluble organic phosphate may also be absorbed, but generally they are of minor importance under most soil conditions. Concentration of the orthophosphate ions in the soil and maintenance of suitable concentration are of greatest importance to plant growth (Robert, 2002).

Phosphorus is needed in cell division, the formation of fat, seed germination, fruiting and flowering, the transformation of starch to sugar and in fact every phase of the plant vital processes (Saucchelli, 1965). It is intimately connected with the utilization of starch and sugar.

Starch may be formed without P but is not readily changed into sugar. Phosphorus is also involved in photosynthesis (Albaum, 1952).

Phosphorus is absorbed by plant roots and then distributed to every living cell in the plant. A seed must contain enough P and other vital nutrients to suffice until roots are formed to obtain a supply from the soil. Phosphorus in the cell becomes united with carbon, hydrogen, oxygen, nitrogen and other elements to form complex organic molecules. It is an essential component of the genetic material of the cell nucleus. Cells cannot divide unless there is adequate P to form the extra nucleus.

Phosphorus has the very important capacity of forming bonds of more than one energy level. This permits the storage, transfer and release of energy within the plant through such materials as adenosine diphosphate (ADP) and adenosine triphosphate ATP. Lack of P hampers metabolic processes such as the conversion of sugar into starch and cellulose. The resulting build up of sugar often leads to the formation of anthocyanins that show as purple spots or streaks on the leaves. The element is not a component of chlorophyll. High chlorophyll content often results when P is deficient and nitrogen is abundant. The resulting plant is dark green in colour (Thompson and Troeh 1978).

In oil palm, phosphorus deficiency is generally not as easy to recognize as in many other nutrients. Phosphorus deficient plant is usually stunted thin-stemmed, and spindly, but its foliage is often dark, almost bluish green. Thus unless much larger healthy plants are present to make a comparison, P-deficient plants often seem quite normal in appearance. In severe cases, P-deficiency can cause yellowing and senescence of leaves.

Phosphorus is needed in especially large amounts in meristematic tissues, where cells are rapidly dividing and enlarging. Phosphorus is very mobile within the plant, so when supply is short, P in the older leaves is mobilized and transferred to the newer, rapidly growing leaves. Both the purpling and premature senescence associated with P deficiency are therefore most prominent on the older leaves.

2.5 THE EFFECT OF PHOSPHATE ROCKS ON THE GROWTH AND YIELD OF OIL PALM

Oil palm requires a constant supply of available P to maintain rapid growth and development (IMPHOS Annual Report, 2005). The major source of P is PR, with Malaysia becoming the major user of PR for direct application to oil palm (IMPHOS Annual Report, 2005).

In Brazil a single application of PR per ha of land deficient of P gave 100 percent yield increase in oil palm over a period of 6 years (Hartley, 1988). This agrees with the role PR play in increasing yield (ton / ha) by 58 percent of oil palm in Indonesia in a second year following implementation of best management practices (Griffiths and Fairhurst, 2002). According to Zin *et al.* (2005), PR fertilizers have a higher content of calcium ranging from 24 – 33 %. This makes PR beneficial in increasing soil pH and cation exchange capacity (CEC) resulting in yield increases of oil palm. Foster *et al.* (1998) noted that the effects of direct application of PR in mature oil palm under Malaysia soil conditions have been very promising. Similarly, in phosphorus deficient soils of Brazil as pertains in tropical Africa, a large initial application of PR had a superior effect to annual doses of triple superphosphate (IRHO, 1974). Its incorporation ensures a steady supply of P over a long period and also provides a high rooting density to crops (Bolan *et al.*, 1990).

Phosphorus supplied to plants from superphosphate is normally fixed rendering it unusable. This occurs before plants including oil palm have access to P. The slow release of P from PR allows plants good opportunity to access for P before fixation can occur. Additionally, fewer cation nutrients can be bound up by free phosphate ions from PR and its application to the soil can last longer depending on the soil condition (Visker *et al.*, 1994).

When low amounts of PR are added to severely P-deficient soils, the soils adsorb tightly almost all of the dissolved P with very little increase in soil solution P. This results in very little increase in crop production including oil palm. At higher levels of P application, as the solution P increases above the threshold concentration for net P uptake by plants, crop yield rises steeply (Rajan, 1973; Fox *et al.*, 1986).

2.6 FACTORS AFFECTING THE AGRONOMIC EFFECTIVENESS OF PHOSPHATE ROCKS

The main factors that affect the agronomic effectiveness of PR in soils are: reactivity of PRs, soil properties, climatic conditions, crop species and management practices.

2.6.1 Reactivity of PRs

The reactivity of PR is a measure of the rate of dissolution of PR under standard laboratory conditions or in a given soil and under given field conditions (Rajan *et al.*, 1996). It excludes the changes in the rate of dissolution caused by varying soil properties and by plant effects. The chemical composition and particle size of PRs determines their reactivity. Phosphate rocks of sedimentary origin are generally most reactive and, therefore, suitable for direct application.

The chemical properties that influence the reactivity of PRs are phosphate crystal (apatite) structure and the presence of accessory materials, especially calcium carbonate. Increasing the substitution of carbonate to phosphate in the crystal structure generally increases the reactivity of PRs. This substitution results in decreased cell dimensions and also weakening of the apatite crystal structure (Lehr and McClellan, 1972; Chien, 1977). The most reactive PRs are those with a molar $\text{PO}_4:\text{CO}_3$ ratio of 3.5:5.

Calcium carbonate is the most abundant accessory mineral in PRs. As calcium carbonate is more soluble than the most chemically reactive phosphate mineral (Silverman *et al.*, 1952), its dissolution increases the calcium (Ca) concentration and pH at the phosphate mineral surface. Thus, it is not surprising that accessory calcium carbonate can reduce the rate of PR dissolution in some soils (Anderson *et al.*, 1985; Robinson *et al.*, 1992). However, under field conditions, leaching and plant uptake may remove Ca ions. The magnitude of the removal by leaching may vary according to soil and climatic conditions and the mode of PR application. For surface applied fertilizer, the calcium carbonate effect can be minimal even if its content is high, as evidenced for Chatham Rise PR from New Zealand, which contained 27 percent free calcium carbonate (Rajan, 1987). On the other hand, for incorporated PR, more than 15 percent of free calcium carbonate may lessen PR effectiveness in a limed alkaline soil (Habib *et al.*, 1999).

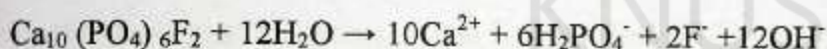
The size of phosphate rocks have important bearing on their rate of dissolution in soil. The finer the particle size, the greater is the degree of contact between PR and soil and, therefore, the higher is the rate of PR dissolution.

2.6.2 Soil properties

For a given PR to be agronomically effective, the PR should not only dissolve, but the dissolved PR should also be available to plants. The soil properties that favour the dissolution of PR are low pH (less than 5.5), low solution concentration of Ca ions, low P fertility levels and high organic matter content (Chien, 1977).

2.6.2.1 Soil acidity

The dissolution of PR may be expressed by the equation:



(Phosphate rock) (Water)

(Dissociation products)

Although the above reaction is for a fluorapatite PR, it applies to other members of the apatite minerals including reactive phosphate rocks (RPRs). As indicated in the above equation, the dissolution of PR results in the release of hydroxyl ions into solution. Neutralization of the hydroxyl ions released by soil acidity enables the PR dissolution process to continue. In the case of PRs where phosphate has been substituted with carbonate ions, hydrogen ions may also be needed to neutralize hydroxyl ions formed on the release of carbonate ions into solution (Chien, 1977). Each carbonate ion (CO_3^{2-}) joins with two hydrogen ions and forms one water molecule and carbon dioxide gas. Thus, an adequate supply of hydrogen ions is of primary importance for the continued dissolution of PR.

Indicators of hydrogen ion supply are soil pH and titratable acidity. Soil pH shows the magnitude of hydrogen ion supply at a given time, whereas titratable acidity indicates the supply of hydrogen ions in the longer term. A linear positive relationship has been reported between initial

pH and titratable acidity in Australian soils (Kanabo and Gilkes, 1987). As a simple guideline, the use of PRs, depending on their reactivity, is generally recommended in soils with a pH of 5.5 or less. The dissolution of PR diminishes with increasing pH up to 5.5 but the decline is more rapid above this pH level (Bolan and Hedley, 1990). When considering a large number of soils, titratable acidity may be a better indicator of PR dissolution (Babare *et al.*, 1997).

2.6.2.2 Cation exchange capacity and exchangeable calcium and magnesium

For continual dissolution of PR, it is important that the other major reaction product, the Ca ion, be removed or that its concentration in soil solution is maintained at a lower level than that in the film surrounding the dissolving PR particle. It is possible to achieve these outcomes if there are adequate soil cation exchange sites available to adsorb the Ca ions released from the PR, or if Ca is leached away from the site of PR dissolution. A measure of the cation exchange sites available for Ca adsorption is the difference between the cation exchange capacity of soils and the exchangeable Ca (Bolan *et al.*, 1990; Robinson and Syers, 1991).

Recent studies suggest that high exchangeable magnesium (Mg) in soils may enhance PR dissolution (Perrott, 2003). Theory would suggest that, as Mg is held by soils more strongly than Ca, the presence of Mg on the soil exchange sites can block adsorption of Ca released on dissolution of PR and thereby facilitate its removal from the soil-fertilizer system. This will have the effect of enhanced PR dissolution. In soils with a low pH (less than 5.5), the exchangeable Ca and Mg will invariably be low (low base saturation) and, therefore, there will be low solution concentrations of these ions.

2.6.2.3 Soil solution P concentration and P retention capacity

As the P concentration in soil solution is usually very low (0.05-0.5 mg/litre), it has little influence on the dissolution of PR. Nevertheless, there have been reports that the greater the P sorption capacity of soils, which results in depletion of soil solution P, the greater the dissolution of PR (Chien *et al.*, 1980). It is not P adsorption capacity per se that affects PR dissolution but the number of sites available to adsorb the P released from PR and, therefore, maintaining a lower P concentration in solution near PR particles.

When considering a large number of soils, the variation in the rate of PR dissolution in soils can be better explained by taking into account the P sorption capacity of soils in addition to the titratable acidity (Babare *et al.*, 1997). Although increased P sorption capacity may favour PR dissolution, its availability will depend on soil P status and the amount of PR added.

2.6.2.4 Soil organic matter

Another soil property that increases PR dissolution and its availability to plants is soil organic matter (Chien *et al.*, 1990). This seems to arise from: (i) the high cation exchange capacity of organic matter, (ii) the formation of Ca-organic-matter complexes and (iii) organic acids dissolving PR and blocking soil P sorption sites.

The cation exchange capacity of organic matter is greater than that for clay minerals. Depending on their clay content, the cation exchange capacity of mineral soils may range from a few to 60 cmol/kg, whereas that of organic matter may exceed 200 cmol/kg (Helling *et al.*, 1964). The high cation exchange capacity of organic matter means increased Ca retention capacity of soils, which leads to enhanced PR dissolution. Humic and fulvic fractions of organic matter form complexes

with Ca (Schnitzer and Skinner, 1969), which can also reduce Ca concentration in solution, so leading to enhanced PR dissolution.

2.6.3 Climatic conditions

Rainfall is the most important climate factor that influences PR dissolution and its agronomic effectiveness. Increased soil water brought about by rainfall or irrigation increases PR dissolution (Weil *et al.*, 1994). The process is affected by speedy neutralization of the hydroxyl ions released and removal of Ca and other reaction products from the area adjacent to PR particles. Adequate water supply will encourage plant growth and P uptake by plants, so leading to the increased agronomic effectiveness of PRs. For surface applied PRs, experience in Australia and New Zealand indicated an annual rainfall requirement of at least 850 mm for PRs to be agronomically similar to water-soluble fertilizers (Hedley and Bolan, 1997; Sale *et al.*, 1997). However, the rainfall requirement does depend on soil properties.

Temperature has been found to have no significant effect on PR dissolution in soil (Chien *et al.*, 1980). It should be born in mind, however, that the reactions involving the products of the dissolution of apatite in the soil may depend on temperature. For example, Chien (1982) and Barrow (1983) have demonstrated that soil temperature has a marked effect on the rate of P sorption by soil.

2.6.4 Crop species

Plant species differ in their P uptake demand and pattern as well as in their ability to absorb soil solution P (Helyar, 1998; Baligar, 2001). Moreover, plant species show differences in their ability to access sparingly forms of P that are unavailable to other plants (Hocking *et al.*, 1997;

Hinsinger, 1998; Hocking, 2001). Among these, some plants can dissolve and take up the products from PR dissolution (Hinsinger and Gilkes, 1997). For example, perennial pastures, tree crops and plantation crops require a steady supply of P over an extended time span.

Plants can also promote dissolution by producing a high root density in the vicinity of PR particles. It has been suggested by Sale and Mokwunye (1993) that the mechanism whereby high rooting density per se stimulates PR dissolution is probably related to the lowering of the concentrations of Ca^{2+} and H_2PO_4^- in the solution surrounding the surfaces of the PR particles. A number of workers (Deist *et al.*, 1971; Flach *et al.*, 1987) have suggested that high Ca uptake patterns are responsible for improved responses of certain crops to applied PR.

Some plant species (e.g. rapeseed, lupines and pigeon pea) have been studied because of their ability to secrete organic acids that result in an enhanced dissolution of PRs (Jones, 1998; Hoffland, 1992; Adams and Pate, 1992; Ae *et al.*, 1990; Montenegro and Zapata, 2002). Recent studies (Chien, 2003) indicate that reactive PRs may have potential applications even in alkaline soils with organic-acid secreting crops such as rapeseed.

2.6.5 Management practices

Four important management practices that can influence the agronomic effectiveness of PRs are: the placement of PR material in relation to the plants, the rate of application, the timing of application and lime application.

2.6.5.1 Phosphate rock placement

In order to achieve the maximum agronomic effectiveness from PRs, the material should preferably be broadcasted and incorporated uniformly into the surface soil to the required depth.

Incorporation facilitates greater dissolution of PR by increasing contact between the soil and PR particles. Banding of PR is less effective (Khasawneh and Doll, 1978; Sale and Mokwunye, 1993; Chien and Menon, 1995).

2.6.5.2 Rate of PR application

The decision on the rate of PR application needs to be based on the soil P status as indicated by soil testing (Perrott *et al.*, 1993; Perrott and Wise, 2000), and the expected rate of dissolution of PR and its availability to plants (Perrott *et al.*, 1996; Rajan *et al.*, 1996).

2.6.5.3 Timing of PR application

In very acid soils (pH less than 5.5) with a high P retention capacity, the incorporation of PR close to planting time is recommended in order to minimize conversion of dissolved P to plant 'unavailable' forms (Chien *et al.*, 1990). However, in less acid soils (pH of about 5.5-6) with a low P retention capacity, incorporation of PR 4-8 weeks ahead of planting is preferred. This allows time for some dissolution of PR and its subsequent availability to plants. Laboratory experiments have shown that it may take 4-8 weeks for PRs to reach their maximum solubility (Barnes and Kamprath, 1975).

2.6.5.4 Lime application

Growth of plants in acid soils is generally improved by liming the soils. Liming may increase the availability to crops of dissolved P by increasing soil pH and reducing aluminium (Al) toxicity. In view of the above effects ~~where liming~~ is to be done in order to raise soil pH values to 5.5, it can be applied at the same time as the PR application, but preferably not as an admixture with PR. This can eliminate Al toxicity while still encouraging PR dissolution. Where the soil pH is to

be raised above pH 5.5, liming should preferably be done about six months after the incorporation of PR so that PR dissolution is not reduced drastically.

Khasawneh and Doll (1978) compared the effects of CaCO_3 and SrCO_3 in order to separate the effects of the soil pH from that of exchangeable Ca. They showed that plant yield was less depressed with SrCO_3 than with CaCO_3 , attributing the reduced PR dissolution to the combined effect of pH and exchangeable Ca. This demonstrates that lime rates should be chosen with great care as to avoid adverse effects on PR rates in acid soils.

2.7 WAYS OF IMPROVING THE AGRONOMIC EFFECTIVENESS OF PHOSPHATE ROCKS

There are situations where directly applied PRs are not effective. In these cases, it is possible to use various means (biological, physical and chemical) to increase their agronomic effectiveness and thereby make the products more economically attractive.

2.7.1 Biological means

The biological means of enhancing the agronomic effectiveness of PRs applied as phosphate fertilizers are: (i) composting organic wastes with PR (phospho-composts); (ii) inoculation of seeds or seedlings with phosphorus-solubilizing micro-organisms (fungi, bacteria and actinomycetes); and (iii) the inclusion in the cropping system with selected plant species.

2.7.1.1 Phospho-composts

Treating PRs with organic materials and composting them is a promising technique for enhancing the solubility and the subsequent availability to plants of phosphorus (P) from PRs.

Phospho-composting is based on sound scientific principles. During the decomposition of organic materials, intense microbial activity occurs. This results in numerous types of bacteria and fungi that produce a large number of organic acids and humic substances. Some of the most commonly produced organic acids are: citric, malic, fumaric, succinic, pyruvic, tartaric, oxaloacetic, 2-ketogluconic, lacticoxalic, propionic and butyric (Stevenson, 1967).

The enhancement of P release from PRs seems to be a function of the acidification of PR by organic acids and more importantly their chelating ability on calcium (Ca), iron (Fe) and aluminium (Al) (Pohlman and McColl, 1986). The greater ability of organic acids, compared with mineral acids of comparable strength, to release P from RP and the direct evidence of their chelating ability have been documented (Kpombrekou and Tabatabai, 1994). Another important factor in the release of P from RP is the participation of the OH groups in the organic acids. For example, it has been shown that citric acid with three carboxyl (COOH) groups and an OH group was able to dissolve more P from PR than cis-aconitic acid with three carboxyl groups but without the OH group (Kpombrekou and Tabatabai, 1994).

Fulvic acid is the most reactive of the humic substances in adsorbing significant amounts of Ca^{2+} and releasing H^+ ions, thereby enhancing PR dissolution. Humic acid may form complexes with P and Ca, and create a sink for further dissolution of RP (Singh and Amberger, 1990).

An increase in the agronomic effectiveness of PR in phospho-composts over that of directly applied PR can be expected because of its greater water -soluble and citric-soluble P contents, which would be available to plants. Moreover, the soluble P fractions should stimulate root growth and facilitate greater exploitation of P enriched soil (Chien *et al.*, 1987; Rajan and Watkinson, 1992; Habib *et al.*, 1999).

2.7.1.2 Inoculation of seedlings with mycorrhizae fundamentals

In nature, most plant roots form mycorrhizal associations of one kind or another with fungi in soil, with the mycorrhizal fungi performing the function of root hairs. The type of mycorrhiza that improves P uptake by plants is vesicular-arbuscular mycorrhizae (VAM), and the commonly used spore types are *Glomus fasciculatum*, *Glomus mosseae*, *Glomus etunicatum*, *Glomus tenue* and *Giaspora margarita*. Vasicular- arbuscular mycorrhizae fungi infect the cells of the root cortex and form both an internal network of hyphae and an external growth of hyphae (Frossard *et al.*, 1995). They possess special structures known as vesicles and arbuscules. The highly branched arbuscules help in the transfer of nutrients from the fungus to the plant-root cells, and the vesicles are sac-like structures, which store P as phospholipids .

Enhanced P uptake in VAM-infected plants seems to be facilitated by: (i) the fungal hyphae exploring a greater volume of soil for P and also intercepting a greater number of point sources of P; (ii) the fungi dissolving sparingly soluble P minerals (e.g. PR); and (iii) the infected roots increasing the rate of P uptake, by increasing the diffusion gradient by depleting P to lower P concentrations than can non-mycorrhizal roots and by enhancing the transfer of P between living roots and from dying roots to living roots (Bolan and Robson, 1987; Sylvia, 1992; Frossard *et*

al., 1995; Lange Ness and Vlek, 2000; Brundrett, 2002). The P inflow rates of mycorrhizal roots are calculated to be 2-6 times than those of non-mycorrhizal roots (Jones *et al.*, 1998).

Compared with non-mycorrhizal plants, Pairunan *et al.* (1980) have reported that mycorrhizal plants enhance the effectiveness of fertilizers by about 30 percent, including that of PR. As mycorrhizal fungi already infect plants of most families, the aim should be to introduce the most efficient mycorrhizal endophyte into plants. Studies indicate that the introduction of appropriate VAM fungi can increase rice grain yields by three-times compared with uninoculated treatments (Secilia and Bagyaraj, 1992). Arihara and Karasawa (2000) reported that, under field conditions, yield and P uptake by maize were enhanced when grown after the cultivation of mycorrhizal crops.

2.7.1.3 Use of genotypes

Phosphorus uptake efficiency can be enhanced by selecting plant species or genotypes that exhibit several mechanisms for increased P absorption under low P conditions, such as: (i) greater root growth and, thus increased extent of soil exploration (ii) the exuding of proton and organic acids-that increase the solubility of sparingly soluble phosphates by decreasing pH and/or chelation and (iii) the production of elevated levels of phosphatase enzymes that can break down organic P to inorganic P (Miyasaka and Habte, 2001). Another approach is to use plants that are tolerant to AI toxicity (Ishikawa *et al.*, 2000).

Increased soil acidity in the rhizosphere can enhance PR dissolution and its availability to plants. This has been observed directly as increased PR dissolution but more often indirectly as increased P uptake by those plants that acidify the rhizosphere (Bekele *et al.*, 1983; Hedley *et al.*,

1983; Moorby *et al.*, 1988; Gahoonia *et al.*, 1992; Haynes, 1992; Nakamaru *et al.*, 2000). Hinsinger and Gilkes (1995) and Habib *et al.* (1999) have also found enhanced PR dissolution by the rhizosphere of some crop species in alkaline soils.

The roots of some plants (e.g. rape) may also enhance PR dissolution by secreting organic acids, such as malic, citric, oxalic and 2-ketogluconic acids, that can be expected to complex cations of PR (Ca, Al and Fe) in addition to lowering rhizosphere soil pH (Moghim and Tate, 1978; Hoffland *et al.*, 1989; Nakamaru *et al.*, 2000; Montenegro and Zapata, 2002).

A new strategy is to improve existing plant species genetically in order to increase root secretion of organic acids and protons. De la Fuente *et al.* (1997) reported that increased secretion of citrate occurred from roots of tobacco as a result of insertion of a citrate synthase gene from *Pseudomonas aeruginosa*.

2.7.2 Chemical means

The chemical means of enhancing the agronomic effectiveness of PR applied as phosphate fertilizer are: (i) partial acidulation of PR with strong acid and (ii) acidulation through heap leaching.

2.7.2.1 Partial acidulation of phosphate rock

Partially acidulated phosphate rocks (PARRs) are prepared by reacting PRs, usually with H_2SO_4 or H_3PO_4 , in amounts less than that needed to make SSP or TSP, respectively. Partial acidulation of phosphate rocks may offer an economic means of enhancing the agronomic effectiveness of indigenous PR sources that may otherwise be unsuited for direct application. For this reason,

extensive studies have been, and continue to be, conducted internationally (Hammond *et al.*, 1986; Rajan and Marwaha, 1993; Chien and Menon, 1995; Chien, 2003; Zapata, 2003). Partially acidulated phosphate rocks are cheaper than fully acidulated WSP fertilizers because less acid and energy is required per unit of P in the product.

2.7.2.2 Acidulation through heap leaching

Another form of acidulation is heap leaching, a technique described by Habashi (1989, 1994). This technology requires low-carbonate or carbonate-free phosphate ores piled in heaps with an impermeable liner at the bottom. In Zambia, a laboratory leach test (with 1 % sulphuric acid) was conducted with phosphate-rich and Fe-rich residual soils from Nkombwa Hill and after neutralization with 10% hydrochloric acid, the resultant extract contained 15% P_2O_5 , 0.7% Fe, 11% Ca, 6.7% Mg and 7% SO_4 (Borsch, 1988).

2.7.3 Physical means

Another alternative way to enhance the breakdown PR into plant-available P forms has led to an array of physical techniques including (i) compacting PR with super phosphates (ii) use of phosphate rock elemental assemblages (iii) thermal treatment and (iv) mechanical activation.

2.7.3.1 Compacted PR with water-soluble phosphate products

Fertilizers that are similar in chemical composition to PAPRs can be prepared indirectly by compacting dry PR with soluble phosphate fertilizers, such as SSP or TSP, under pressure (Chien *et al.*, 1987; Chien and Menon, 1995; Menon and Chien, 1996). The water-soluble P content of the products will depend on the ratio of PR to WSP fertilizer used. There is evidence that the effectiveness of PRs, even those of low reactivity, is increased after compacting with water

soluble P (Chien *et al.*, 1987; Kpombrekou *et al.*, 1991). Under these conditions, compaction of PR with water-soluble P fertilizers at P ratios of about 50:50 can make the use of indigenous PRs agronomically and economically attractive.

Research conducted on an Indian calcareous soil indicated that applying fertilizers at a single rate in a 1:1 mixture of Mussoorie PR and SSP could be as effective as SSP (Siddique *et al.*, 1986). In another field study, Mussoorie PR and SSP were applied at a P ratio of 2.2:1 using three fertilizer application rates (Singaram *et al.*, 1995). The results showed that in an alkaline soil (pH 8.2) the PR-SSP mixture tended to be as effective as SSP.

2.7.3.2 Phosphate rock elemental sulphur assemblages

Numerous studies have shown that the agronomic effectiveness of PRs can be improved when they are applied after admixing or cogranulating with sulphur (S). In some instances, the products were inoculated with sulphur-oxidizing bacteria *Thiobacillus* spp. Thus, the product was referred to as 'biosuper' (Swaby, 1975).

Research shows that the PR/S prepared from a finely ground reactive North Carolina PR, at a PRS ratio of 5:1, was as effective as SSP, whereas that prepared from an unreactive Florida PR was inferior. Nevertheless, there was an increase in the agronomic effectiveness of both PRs when they were applied as PR/S, the values being 18-30 percent for the North Carolina PR and 50-70 percent for the Florida PR depending on the rate of application (Rajan, 1982).

2.7.3.3 Thermal treatment

The best known thermal phosphates are Rhenania phosphates and fused magnesium phosphate. The Rhenania process entails mixing soda ash (Na_2CO_3) with PR with silica and subjecting it, in the presence of steam to temperatures between 1100 and 1200 $^{\circ}\text{C}$. Rhenania phosphates have high solubilities and are suitable for tropical soils. It is alkaline in reaction and can be used as liming material in acid soils.

Fused magnesium phosphates are formed by mixing PR with Mg sources such as olivine or serpentine under high temperature (1500-1600 $^{\circ}\text{C}$). It has successfully been field tested in Brazil (Cekinski and da Silva, 1998) and in Zambia (Goma *et al.*, 1991). The advantage of the thermal technique is that low reactive PRs or Al-phosphates that would otherwise be ineffective when applied directly to the soil can be used.

2.7.3.4 Mechanical activation

Gock and Jacob (1984) proposed another way of processing low reactive PRs. They tested a rotary-Chamber vibrating mill for sedimentary phosphate rock from Egypt. This dry milling technique not only reduces the grain size of the PR considerably, but it opens up defect sites in phosphate minerals and subsequently changes the solubility parameters of the PR as a function of milling time. X-ray diffraction and infra-red data reported by citrate solubility test over time provide evidence for mineralogical changes that enhance solubility of the PR (Gock and Jacob, 1984).

2.8 Literature review summary

Some salient points highlighted in the review are problems of soil fertility, more especially phosphorus (P) deficiency probably due to low solution P concentration and a high P sorption capacity in areas climatically suitable for oil palm cultivation in Ghana. This P-deficiency under oil palm has greatly been reduced in the Far-East (Malaysia and Indonesia) through direct application of phosphate rocks (PRs) resulting in corresponding increase in oil palm yields. Directly applied PRs are influenced by certain factors including reactivity of PRs, soil properties, climatic conditions, crop species and management practices. Also its agronomic effectiveness are greatly enhanced through biological (phospho-compost, use of genotypes and inoculation of seedlings with mycorrhizae fundamentals), chemical (partial acidulation of PR with acid and acidulation through heap leaching) and physical means (compacted PR with water soluble phosphate products, phosphate rock elemental sulphur assemblages, thermal treatment and mechanical activation).



CHAPTER THREE

MATERIALS AND METHODS

3.1 LOCATION OF THE STUDY AREA

The study was conducted from 2003 to 2007 at the Oil Palm Research Institute (OPRI), Kusi, which is about 11 km away from Kade (Kwaebibirim district capital). The area lies between latitudes 06° 02' and 06° 05' North and longitudes 00° 52' and 00° 54' West of Greenwich meridian, with an elevation of 164 m above sea level in the Eastern Region of Ghana.

3.2 CLIMATE OF THE STUDY AREA

The study area falls within the semi-deciduous forest zone of Ghana (Taylor, 1952). The area is in a zone characterized by relatively high rainfall which falls in two seasons (bi-modal). The mean annual rainfall is 1125 mm. The major rainy season starts from April to July and the minor season starts from September to mid-November. The major dry season occurs between the end of the minor wet season and the next major wet season. Temperatures are generally high and uniform throughout the year. The mean monthly temperatures range from 24 – 30 °C. The month of July records the lowest mean monthly temperature of about 24 °C, while March records the highest of 30 °C.

The relative humidity is generally high in the mornings being about 90% at 0600 hours and falling to between 60 and 70% in the afternoon (1500 hours). Generally, in the wet season relative humidity is high (about 95%), while it is low (about 40%) in the dry season.

3.3 SOILS OF THE STUDY AREA

The experiment was carried out on soils of Nzima series classified by Adu (1992) as Ferric Acrisols according to FAO (1990) and Typic Hapludult according to USDA (1991).

3.4 EXPERIMENTAL DESIGN AND TREATMENTS

The experiment was conducted in randomized complete block design (RCBD) with 4 treatments in 3 replications. The oil palm trees selected were 8 year old tenera (D x P ex OPRI). Each plot measured 17.6 x 17.6 m and had 6 palms. Planting was done at a spacing of 8.8 m triangular or the equivalent of 148 palms per hectare. The treatments evaluated are as follows:

TSP - OPRI fertilizer recommendation- 222 kg of AS + 222 kg of TSP + 296 kg of MOP / ha / yr (equivalent to 46 kg N + 102 kg P_2O_5 + 177 kg K_2O / ha / yr) – Control

PR1 - PR 715 kg + 222 kg of AS + 296 kg of MOP / ha / yr (equivalent to 200 kg P_2O_5 + 46 kg N + 177 kg K_2O / ha) – Yr 1

PR 358 kg + 222 kg of AS + 296 kg of MOP / ha (equivalent to 100 kg P_2O_5 + 46 kg N + 177 kg K_2O / ha) – Yr 2

PR 358 kg + 222 kg of AS + 296 kg of MOP / ha (equivalent to 100 kg P_2O_5 + 46 kg N + 177 kg K_2O / ha) – Yr 3

PR2 - PR 1428 kg + 222 kg of AS + 296 kg of MOP / ha (equivalent to 400 kg P_2O_5 + 46 kg N + 177 kg K_2O / ha) applied once in every 5 years.

PR3 - PR 142.85 kg / ha + 222 kg AS / ha + 296 kg of MOP / ha (equivalent to 40 kg

P_2O_5 , 46 kg N and 177 kg K_2O) applied twice in every 5 years, MOP .

(In the above treatments, AS = ammonium sulphate, TSP = triple super phosphate, MOP = muriate of potash and PR = Phosphate rock).

Treatment plots were broadcasted with appropriate straight fertilizers individually within the interrows and rings of palm trees (1.5 m radius around the palm - Plate: 7). These fertilizers were later worked into a depth of about 3 cm to ensure better contact with soil particles.

3.5 CROP MANAGEMENT

For effective growth and development of palms, the following management practices were carried out as and when necessary.

i. Cover cropping

Plots were cultivated with leguminous cover crop *Pueraria phaseoloides* at a seeding rate of 0.5 kg per plot. This was to check erosion, keep soil friable, improve soil structure, reduce leaching and suppress weeds.

ii. Pruning

Judicious removal of non-functional fronds was carried out annually with a pruning cutlass. Pruning provided ready assess for harvesting and reduced the loose fruits trapped in the frond bases.

iii. Diseases and pest control

Phytosanitary inspectors routinely carried out visits to site to control pest and disease.

iv. Weed control

Both ring weeding and interrow brushing were carried out quarterly. Ring weeding was done with a cutlass 1.5 m radius around the palm base. Interrow brushing was also carried out to lessen competition between palms and weeds.

3.6 ANALYTICAL METHODS

The chemical and physical properties of the soils used were determined in the laboratory of Soil Research Institute, Kwadaso – Kumasi. Samples were taken with soil augar from the palm circle and interrow at depths of 0-15 cm and 15-30 cm. The soil samples were air-dried, crushed and sieved through 2mm mesh sieve before analysis.

3.6.1 Soil pH

Soil pH was determined in a 1:2.5 suspension of soil and water using a HI 9017 Micro-processor pH meter. A 20 g soil sample was weighed into 100 ml polythene bottle. To this 50 ml distilled water was added from a measuring cylinder and the bottle capped. The solution was shaken on a reciprocating shaker for thirty minutes. After calibrating the pH meter with buffer solutions at pH 4.0 and 7.0, the pH was read by immersing the electrode into the upper part of the suspension.

3.6.2 Soil organic carbon and organic matter

Soil organic carbon was determined by a modified Walkley and Black procedure as described by Nelson and Sommers (1982). This procedure involves a wet combustion of the organic matter with a mixture of potassium dichromate and sulphuric acid. After reaction, the excess dichromate is titrated against ferrous sulphate. One gram of soil sample was weighed into an

erlenmeyer flask. A reference sample and a blank were included. Ten milliliters of 1.0 N (equivalent to 0.1667 M) potassium dichromate solution was added to the soil and the blank flask. To this, 20 ml of concentrated sulphuric acid was carefully added from a measuring cylinder, swirled and allowed to cool for 30 minutes in a fume cupboard. Distilled water (250 ml) and concentrated orthophosphoric acid (100 ml) were added and allowed to cool. One millilitre of diphenylamine indicator was added and titrated with 1.0 M ferrous sulphate solution.

Calculation:

The organic carbon content of the soil is:

$$\% \text{ Organic C} = \frac{M \times 0.39 \times \text{mcf} (V_1 - V_2)}{s}$$

where:

M = molarity of ferrous sulphate solution

V₁ = ml ferrous sulphate solution required for blank

V₂ = ml ferrous sulphate solution required for sample

s = weight of air-dry sample in gram

mcf = moisture correcting factor (100 + % moisture) / 100

0.39 = 3 x 0.001 x 100% x 1.3 (3 = equivalent weight of C).

1.3 = a compensation factor for the incomplete combustion of the organic matter.

3.6.3 Total nitrogen

Total nitrogen was determined by Kjeldahl digestion and distillation procedure as described by Soil Laboratory Staff (1984). A 0.5 g soil sample was put into a Kjeldahl digestion flask and 5 ml distilled water added to it. After 30 minutes, 5 ml concentrated sulphuric acid and selenium mixture were added and mixed carefully. The sample was heated on a Kjeldahl digestion apparatus for 3 hours until a clear digest was obtained. The digest was diluted with 50 ml distilled water and mixed well until no more sediment dissolved and allowed to cool. The volume of the solution was made to 100 ml with distilled water and mixed well. A 25 ml aliquot of the solution was transferred to the reaction chamber and 10 ml of 40% NaOH solution was added followed by distillation. The distillate was collected in 2% boric acid. The distillate was titrated with 0.02N HCl solution with bromocresol green as indicator. A blank distillation and titration was also carried out to take care of traces of nitrogen in the reagents as well as the water used.

Calculation:

The % N in sample was expressed as:

$$\% N = \frac{M \times (a - b) \times 1.4 \times mcf}{s}$$

where:

M = concentration of HCl used in titration

a = ml HCl used in sample titration

b = ml HCl used in blank titration

s = weight of air-dry sample in gram

mcf = moisture correcting factor $(100 + \% \text{moisture})/100$

$$1.4 = 14 \times 0.001 \times 100\% \text{ (14 = atomic weight of nitrogen)}$$

3.6.4 Bray No. 1 phosphorus (available phosphorus)

The readily acid – soluble form of phosphorus was extracted with a HCl: NH_4F mixture called the Bray's No. 1 method as described by Bray and Kurtz (1945) and Olsen and Sommers (1982). Phosphorus in the extract was determined on a spectrophotometer by the blue ammonium molybdate method with ascorbic acid as reducing agent.

A 2.0 g soil sample was weighed into a shaking bottle (50 ml) and a 20 ml of extracting solution of Bray-1 (0.03 M NH_4F and 0.025 M HCl) was added. The sample was shaken for one minute by hand and then immediately filtered through a fine filter paper (Whatman No. 42). One ml of the standard series, the blank and the extract, 2 ml boric acid and 3 ml of the coloring reagent (ammonium molybdate and antimony tartarate solution) were pipetted into a test tube and homogenized. The solution was allowed to stand for 15 minutes for the blue colour to develop to its maximum. The absorbance was measured on a spectronic 21D spectrophotometer at 660 nm wavelength. A standard series of 0, 1.2, 2.4, 3.6, 4.8 and 6 mg P/L was prepared from a 12 mg/L stock solution by diluting 0, 10, 20, 30, 40 and 50 ml of 12 mg P/L in 100 ml volumetric flasks and made to volume with distilled water. Aliquots of 0, 1, 2, 3, 4, 5 and 6 ml of the standard solution were put in 100 ml volumetric flasks and made to the 100 mg P/L of the standard solution were put in 100 ml volumetric flasks and made to the 100 ml mark with distilled water.

Calculation:

$$P \text{ (mg/kg)} = \frac{(a-b) \times 20 \times 6 \times mcf}{s}$$

where: _____

a = mg/l P in a sample extract

b = mg/l P in the blank

s = sample weight in grams

mcf = moisture correcting factor

20 = ml extracting solution

6 = ml final sample solution

3.6.5 Available potassium (K)

A 20 ml aliquot of the extract was used for the available K. The K values were determined using emission values of the Gallenkamp flame analyzer. A standard series of 0, 1.2, 2.4, 3.6, 4.8, and 6.0 mg was prepared from a 12 mg K/l stock solution by diluting 0, 10, 20, 30, 40 and 50 ml of 12 mg P/l in 100 ml volumetric flask and made to the volume with distilled water.

Calculations:

$$K \text{ (mg/kg)} = \frac{(a - b) \times 20 \times 6 \times \text{m.c.f}}{S}$$

Where

a = mg/l K in sample extract

b = mg/l K in blank

S = sample weight (g)

m.c.f = moisture correction factor

20 = extracting solution (ml)

6 = final sample solution (ml)

3.6.6. Exchangeable cations

Exchangeable bases (calcium, magnesium, potassium and sodium) in the soil were determined in 1.0 *M* ammonium acetate (NH_4OAc) extract (Black, 1986) and the exchangeable acidity (hydrogen and aluminium) was determined in 1.0 *M* KCl extract as described by Page et al. (1982).

3.6.6.1 Extraction of the exchangeable bases

A 10 g sample was transferred into a leaching tube and leached with 250 ml of buffered 1.0 *M* ammonium acetate (NH_4OAc) solution at pH 7.

3.6.6.2 Determination of calcium and magnesium

For the determination of the calcium plus magnesium, a 25 ml portion of the extract was transferred into an Erlenmeyer flask and the volume made to 50 ml with distilled water. A 1 ml portion of hydroxylamine hydrochloride, 1 ml of 2.0 percent potassium cyanide (from burette), 1 ml of 2.0 per cent potassium ferrocyanide, 10 ml ethanolamine buffer and 0.2 ml Eriochrome Black T solution was added. The solution was titrated with 0.01 *M* EDTA (ethylene diamine tetraacetic acid) to a pure turquoise blue colour. A 20 ml 0.01 *M* magnesium chloride solution was also titrated with 0.01 *M* EDTA in the presence of 25 ml of 1.0 *M* ammonium acetate solution to provide a standard blue colour for the titration.

3.6.6.3 Determination of Calcium only

A 12.5 ml of the ~~extract was transferred into an erlenmayer flask~~ and the volume made to 25 ml with distilled water. Hydroxylamine hydrochloride (1 ml) potassium cyanide (1 ml of 2% solution) and potassium ferrocyanide (1 ml of 2%) were added. After a few minutes, 4 ml of 8 *M*

potassium hydroxide and a spatula of murexide indicator were added. The solution obtained was titrated with 0.01M EDTA solution to a pure blue colour. Twenty millilitres of 0.01 M calcium chloride solution was titrated with 0.01 M EDTA in the presence of 25 ml 1.0 M ammonium acetate solution to provide a standard pure blue colour.

Calculation:

The calculation of the concentration of calcium + magnesium or calcium follows the equation:

$$\text{Ca+Mg (or Ca) (cmol/kg soil)} = \frac{0.01 \times (V_a - V_b) \times 1000}{0.1 \times w}$$

Where:

w = weight in grams of soil of oven – dry soil extracted

V_a = ml of 0.01 M EDTA used in titration

V_b = ml of 0.01 M EDTA used in blank titration

0.01 = concentration of EDTA used

$$\text{Ca = Mg or (Ca) (cmol/kg soil)} = \frac{0.01 \times (V_a - V_b) \times 1000}{0.1 \times w}$$

3.6.6.4 Determination of exchangeable potassium and sodium

Exchangeable potassium and sodium in the solution were determined by flame photometer using 10mls of aliquot from the leaching tubes to read the emission values. Standard series of potassium and sodium were prepared by diluting both 1000 mg/l potassium and sodium solutions to 100 ml/l. This was done by taking a 25 ml portions of each into one 250 ml volumetric flasks

and made to volume with distilled water. Portions of 0, 5, 10, 15 and 20ml of the 100 mg/l standard solution were put into 200 ml volumetric flasks respectively. One hundred millilitres of 1.0 M NH₄OAc solution was added to each flask and made to volume with distilled water. The standard series obtained were 0, 2.5, 5.0, 7.5, 10.0 mg/l for potassium and sodium. Potassium and sodium were measured directly in the percolate by flame photometry at wavelengths of 766.5 and 589.0 nm respectively.

Calculation:

$$\text{Exchangeable K (cmol/kg soil)} = \frac{(a - b) \times 250 \times mcf}{10 \times 39.1 \times s}$$

$$\text{Exchangeable Na (cmol/kg soil)} = \frac{(a - b) \times 250 \times mcf}{10 \times 23 \times s}$$

Where:

a = mg/l K or Na in the diluted sample percolate

b = mg/l K or Na in the diluted blank percolate

s = air-dried sample weight of soil in gram

mcf = moisture correcting factor

3.6.6.5 Total Exchangeable Bases (T.E.B.)

Total exchangeable bases is the sum of all the basic cations (Ca²⁺, + Mg²⁺ + K⁺ + Na⁺).

3.6.6.6 Exchangeable acidity

Exchangeable acidity is the sum of Al + H. The soil sample was extracted with unbuffered 1.0 M KCl and the sum of Al+H was determined by titration. Fifty grams of soil sample was put in a

200 ml plastic bottle and 100 ml of 1.0 M KCl solution added. The bottle was capped and shaken for 2.0 hours and then filtered. Fifty millilitres portion of the filtrate was taken with a pipette into a 250 ml erlenmeyer flask and 2 drops of phenolphthalein indicator solution added. The solution was titrated with 0.1 M NaOH until the colour just turned permanently pink. A blank was included in the titration.

Calculation:

$$\text{Exchangeable acidity (cmol/kg soil)} = \frac{(a - b) \times M \times 100 \times \text{mcf}}{s}$$

a = ml NaOH used to titrate with sample

b = ml NaOH used to titrate with blank

M = molarity of NaOH solution

s = air – dried soil sample weight in grams

mcf = moisture correction factor $(100 + \% \text{ moisture}) / (100)$.

3.6.6.7 Effective Cation Exchange Capacity (ECEC)

Effective cation exchange capacity was calculated by the sum of all the exchangeable bases (Mg^{2+} , Ca^{2+} , K^{+} and Na^{+}) and exchangeable acidity. ($\text{Al}^{3+} + \text{H}^{+}$).

3.6.6.8 Percentage Base Saturation (% BS)

This is the total exchangeable bases express as percentage over the ECEC.

$$\% \text{ BS} = \frac{\text{TEB}}{\text{ECEC}}$$

3.6.6.9 Particle size analysis

The hydrometer method (Bouyoucos, 1962) was used to determine the texture of the soil. A 50 g soil sample was weighed in a graduated cylinder. The soil was saturated with distilled water and 100 ml of 10% calgon (sodium hexametaphosphate) and stirred for 10 minutes. The suspension was transferred to a 1000 ml cylinder and filled with distilled water to the mark. Two drops of amyl alcohol were added. The suspension was mixed thoroughly with a long glass rod and the temperature read. The hydrometer was gently lowered into the suspension. The hydrometer readings were taken at 30 seconds and 3 hours.

Calculation:

$$\% \text{ silt} = F_1/M \times 100$$

$$\% \text{ clay} = F_2 \times 100/M$$

$$\% \text{ sand} = 100 \% - (\% \text{ silt} + \% \text{ clay})$$

Where

F_1 = corrected first hydrometer reading

F_2 = corrected second hydrometer reading

M = mass of dry soil (50g)

The texture was determined by interpolating the sand, silt and clay percentages in a textural triangle.

3.7 SOIL MICROBIAL BIOMASS ANALYSIS

3.7.1 Soil microbial biomass carbon and nitrogen

The method of chloroform fumigation and extraction (FE) as described by Ladd and Amato (1989) was used to determine microbial biomass. Two 10 g field moist soil samples after passing through a 4 mm mesh, was put in 50 ml beakers and placed in large jars (1.0L).

A small beaker containing 10 ml of chloroform was put by one of the soil samples in the jar. A sample without chloroform served as control. The jars were covered and allowed to stand at room temperature for 48 hrs. Immediately after fumigation a 100 ml 0.5 M K_2SO_4 solution (Tate *et al.*, 1988; Joergenson and Brookes, 1990) was used to extract microbial carbon from the lysed microorganisms. The amount of microbial carbon in solution was determined after an aliquot of the extracted microbial carbon had been evaporated to dryness. The dichromate oxidation was used. Total nitrogen was determined by the Kjeldahl method in the same extract. For biomass C and N calculations, k-factors of 0.35 (Sparling *et al.*, 1990) and 0.45 (Jenkinson, 1988; Ross and Tate, 1993) were used, respectively. The following equation was used to estimate the microbial carbon and nitrogen from the extracted carbon:

$$\text{Microbial C or N } (\mu\text{g}) = E_c/k \quad (\text{Sparling and West, 1988})$$

where:

E_c = the extracted carbon produced following fumigation

k = the fraction of the killed biomass extracted as carbon or nitrogen under laboratory conditions.

3.7.2 Soil microbial phosphorus

Microbial P was determined by the chloroform fumigation extraction method allowing for correction of P sorption occurring during fumigation and extraction (Gijsman *et al.*, 1997). The fumigated samples were extracted with the Bray-1 solution. Correction for adsorption of P during fumigation was made by simultaneously equilibrating unfumigated soil with a series of P containing standard solutions followed by extraction with the Bray-1 solution. The amount of chloroform released P added (from standard solutions or microbial lysis) and P extracted by the Bray-1 solution (Oberson *et al.*, 1997). P adsorption during equilibrium is described by the following equation according to Barrow and Shaw (1975) and adapted by Morel *et al.* (1997):

$$\text{Ext}_p = \text{Ext}_0 + b_1 P_{ad}^{b_2}$$

where:

Ext_p = Pi concentration (mg/l) extracted after equilibration with different amounts of P added,

Ext_0 = Pi concentration extracted without P addition,

b_1, b_2 = coefficients estimated by non-linear regression of mean values of Ext_p against P_{ad} .

P_{ad} = amount of P added (0 – 20 mg/kg).

Chloroform released P corresponds to a P addition and is calculated from the equation:

$$P_{chl.} = [(\text{Ext}_{chl.} - \text{Ext}_0)/b_1]^{1/b_2}$$

where:

$P_{chl.}$ = chloroform released P (mg/kg),

$Ext_{chl.} = P_i$ concentration in extracts of fumigated samples.

The amount of microbial P is estimated by assuming a Kp factor of 0.4 (Brookes *et al.*, 1982; McLaughlin and Alston, 1986).

3.8 PHOSPHATE ROCK AND TRIPLE SUPER PHOSPHATE CHARACTERIZATION

3.8.1 Determination of total phosphorus in phosphate rock and triple super phosphate

Total P in each phosphorus fertilizer material was determined by weighing 0.1 g of the sample into a clean micro Kjeldahl flask. Five millilitres of concentrated HCl was added to the sample and warmed to gently dissolve. The flask was allowed to cool. Distilled water was added and the sample shaken after which it was filtered through a Whatman No. 42 filter paper into 250 ml volumetric flask. The filtrate was diluted to 500 ml with distilled water. Phosphorus in filtrates from phosphate rock and triple super phosphate was determined using the ammonium molybdate-ascorbic method (Watanabe and Olsen, 1965) as follows:

Suitable aliquots (5 ml) of each filtrate were taken (in duplicate) into 50 ml volumetric flasks containing distilled water. The pH was adjusted using P-nitrophenol indicator and neutralized with few drops 4M ammonium hydroxide (NH_4OH) until the solution turned yellow. The solution was diluted to about 40 ml with distilled water after which 8 ml of reagent A (ascorbic acid + ammonium molybdate + antimony potassium tartarate + concentrated sulphuric acid in distilled water) was added and made to volume with distilled water. The solution was mixed thoroughly by shaking and allowed to stand for 15 minutes for the blue colour to stabilize. A blank was prepared with distilled water and 8 ml of reagent A. The method was calibrated using a standard solution of 25 mg P/l. The intensity of the blue colour was measured using the Philips PU 8620 spectrophotometer at a wavelength of 712 nm and the P concentrations read on a

standard curve prepared with aliquots of a KH_2PO_4 standard solutions containing 5, 10, 15, 20, 25, 30, 35, and 40 mg P/l.

3.8.2 Solubility of phosphate rock and triple super phosphate

The solubility of phosphorus fertilizer sources used was determined in neutral ammonium citrate (NAC) and water (Chien and Hammond, 1978). One g of each fertilizer material was weighed into 150 ml extraction bottles and 100 ml of each of the extractants added. The suspension was shaken for 1 hour and filtered through a No. 6 Whatman filter paper. The filtrates obtained for triple super phosphate and phosphate rock were diluted to 1000 ml and 2 ml of the diluted solution (taken in duplicate for each extractant) used to determine the P concentration. For the filtrate obtained from the phosphate rock, 5 ml aliquot was used to determine the P concentration using the ammonium molybdate ascorbic acid method as described under 3.8.1.

3.9 LEAF NUTRIENT DYNAMICS

To determine the dynamics of oil palm nutrient content, leaf samples of the oil palm lamina from the central leaflets of leaf No. 17 were taken annually from each of the treatments. Leaf samples were cleaned thoroughly with cotton wool and distilled water. They were oven dried at temperature of 70°C for 48 hours to a constant weight. The oven dried leaf samples were milled to pass through 0.5 mm sieve mesh and used for the determination of total nitrogen, phosphorus, potassium, calcium and magnesium.

3.9.1 Total plant nitrogen

Total nitrogen was determined with Kjeldahl digestion and distillation method as described by Soil Laboratory Staff (1984).

3.9.2 Total phosphorus, potassium, calcium and magnesium

Half a gram (0.5g) of ground leaf sample was ashed in a muffle furnace for 4 hours at a temperature of 450 °C. The ashed leaf was dissolved in 1.0 M HCl solution and filtered through No. 42 filter paper. The filtrate was diluted to 100 ml with distilled water.

3.9.3 Total phosphorus determination

A 5.0 ml aliquot of the filtrate was taken into a 25 ml volumetric flask. Following this, 5.0 ml of ammonium vanadate and 2.0 ml stannous chloride solutions were added and made to the 25 ml mark with distilled water. The solution was allowed to stand for 10 minutes for full colour development. A standard curve was also developed concurrently with phosphorus concentrations ranging from 0, 1, 2, 5, 10, 15, to 20 mg P/L. The absorbance of the sample and standard solutions were read on the spectrophotometer (Spectronic 21 D) at a wavelength of 470 nm. A standard curve was obtained by plotting absorbance values of the standard solutions against their concentrations. Phosphorus concentration of the samples were determined from the standard curve.

3.9.4 Total potassium

Potassium in the filtrate was determined using a Gallenkamp flame analyzer. Potassium standard solutions were prepared with the following concentrations: 0, 10, 20, 40, 60 and 100 mg K/L of solution. The emission values were read on the flame analyzer. A standard curve was obtained by plotting emission values against their respective concentrations.

3.9.5 Total calcium and magnesium

A 10.0 ml aliquot of the filtrate was pipetted into an erlenmeyer flask. Potassium cyanide and potassium ferrocyanide solutions were added to complex (remove) interfering cations such as Cu and Fe. In the Ca + Mg determination, the solution was titrated with 0.01 M EDTA solution in the presence of murexide indicator. To determine the sum of calcium and magnesium content, potassium hydroxide was added to raise pH to about 12. At this pH, magnesium is precipitated leaving calcium in the solution. The solution was titrated again with EDTA using Eriochrome Black T as the indicator. The difference between the first and second titres represents magnesium concentration in the solution.

3.10 Rainfall data

Rainfall data was collected for the site (Appendix 3). Monthly and annual water deficits were calculated from the rainfall data using the formula:

$$D = R + P - Pe$$

Where:

D = Water deficits; R = Theoretical soil moisture reserve at the end of the previous month; P = precipitation or rainfall for the month; Pe = potential evapotranspiration for the month (Surre, 1968).

3.11 GROWTH, DEVELOPMENT AND YIELD OF OIL PALM

The growth data were taken by using the appropriate instruments in March and October annually and the mean of the two measurements were computed to represent the annual data.

i. Leaf area per palm (LA)

Three leaflets were selected from the centre of either side of frond No. 17. The width (W) and the length (L) of leaflets were taken with a ruler (Plate: 1 and 2). The width was taken at the center. The LA was computed by putting measurements acquired in an equation developed by Harden *et al.* (1969) as shown below:

$$LA = b (n \times LW)$$

Where:

n = number of leaflets, LW = mean of length x mid – width for a sample of the largest leaflets, and b, the correction factor = 0.55.

ii. Leaf area index (LAI)

Having estimated the leaf area (LA) of a palm, it was related to the ground area. LAI was thus estimated by the formular as shown below by Harden *et al.* (1969):

$$LAI = \frac{\text{Leaf area}}{\text{Ground area}}$$

iii. Frond dry weight (FDW)

A non-destructive method by Corley (1971) was used to estimate this parameter. The method allows for the estimation of a dry matter production rates. A pair of calipers was used to measure the width and depth of the petiole of frond no. 17 (Plate: 3 and 4) and values obtained were put into a formula to estimate the FDW (Corley 1971) as follows:

$$FDW = 0.1023 \text{ width} \times \text{depth} + 0.2362 \text{ (Kg)}$$

0.1023 and 0.2062 (kg) = correction factors (Harden *et al.*, 1969)

vi. Plant height

The plant height was measured with graduated measuring pole from the base of the palm to the point of insertion in the axil of leaf No. 33 (Plate 5).

vii. Yield of oil palm

Weekly individual recording of fresh fruit bunches (FFB) was carried out. Weighing of fresh fruit bunches was done with a weighing scale at the field immediately after harvesting (Plate 8). The weight and numbers of the FFB harvested were recorded for individual palms at each harvesting round. The data obtained was used to estimate yield in tons per hectare.

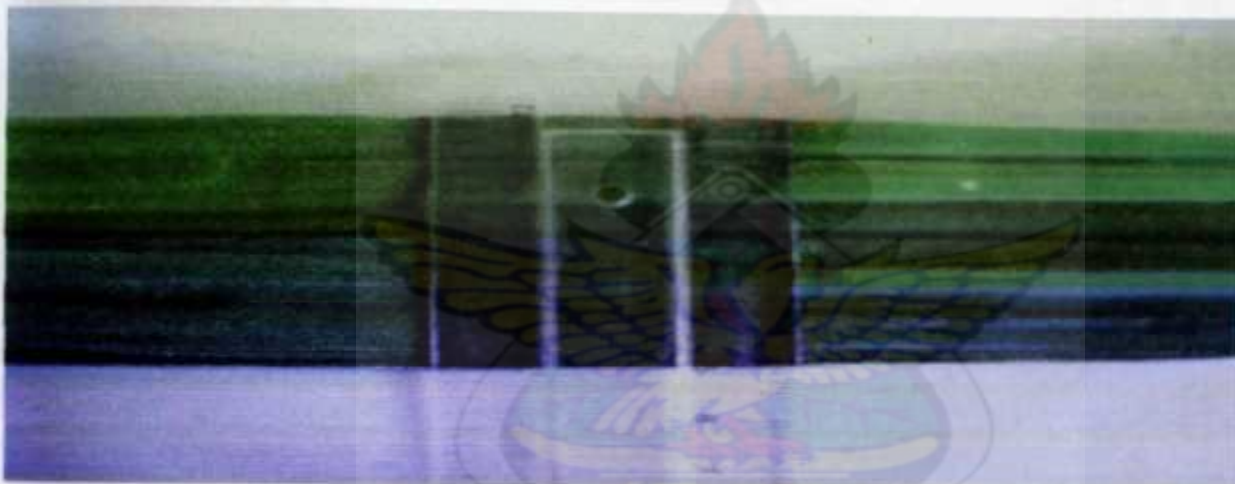


Plate 1: Leaflet width measurement with ruler

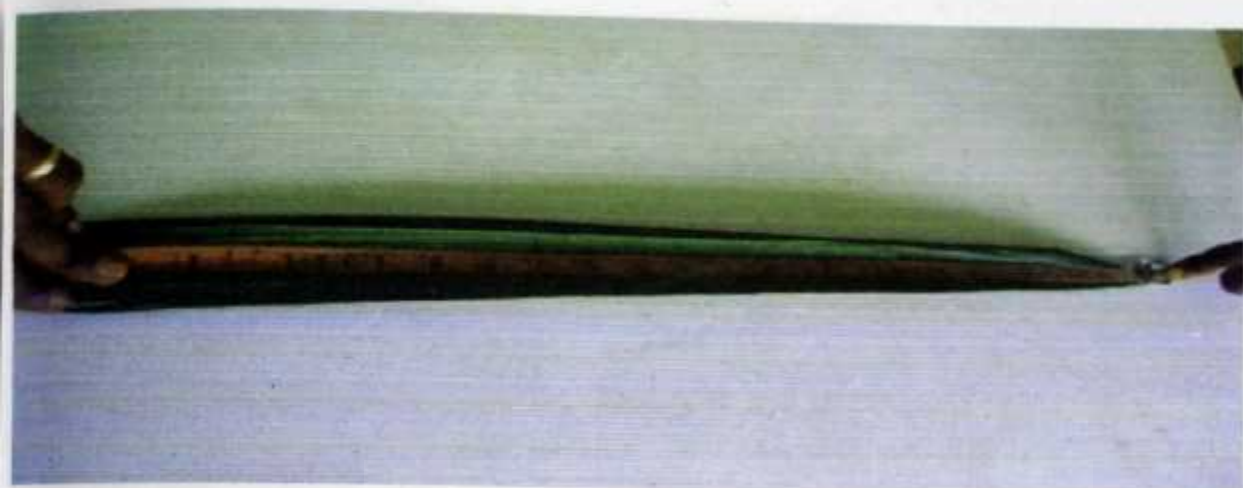


Plate 2: Leaflet length measurement with measuring tape



Plate 3: Frond dry weight width measurement with venier caliper

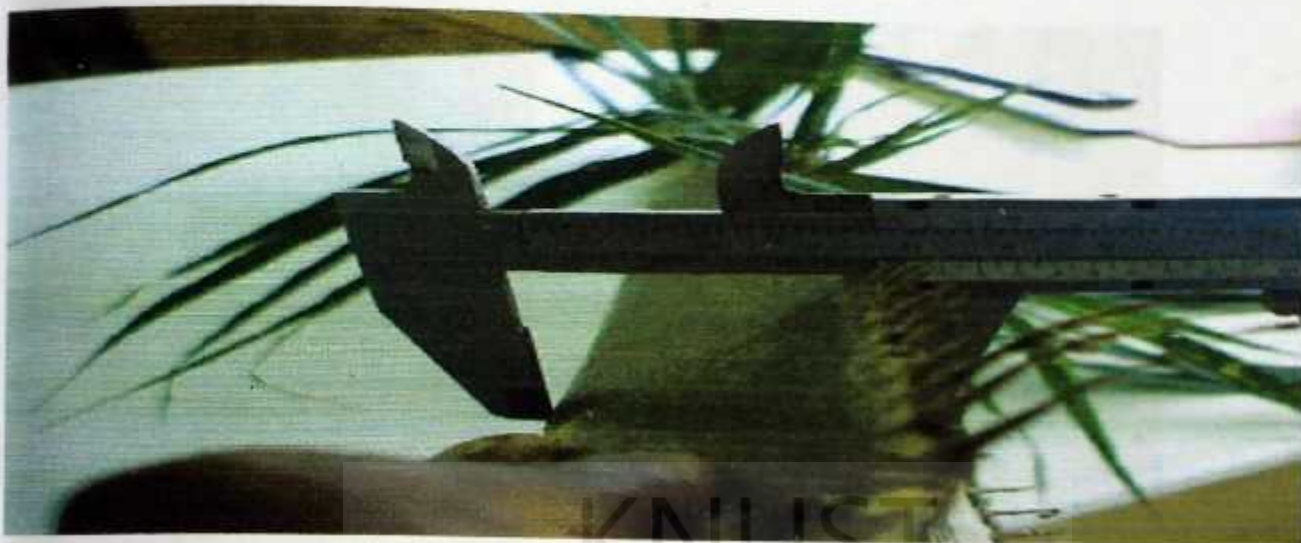


Plate: 4 Frond dry weight depth measurement with venier caliper



Plate 5: Height measurement



Plate 6: Cutting of frond No. 17



Plate: 7 Ring fertilizer application



Plate 8: Weighing of fresh fruit bunch

3.12 RELATIVE INCREASE (RI %)

The relative yield increase of PR treatments relative to OPRI recommendation (control) was calculated as:

$$RI = \frac{(Y_{pr} - Y_{OPRI})}{Y_{OPRI}} \times 100$$

where:

Y_{pr} = Yield in tons/ha from phosphate rock plots and Y_{opri} = Yield in tons/ha from control plot (TSP).

3.13 AGRO-ECONOMIC ANALYSIS

The cost benefit analysis of treatments was carried out by comparing production cost and revenue generated by OPRI fertilizer recommendation (control) with PR treatments. Data was kept on cost of materials and labour used for the experiment. Labour cost at the period of study was used as well as the OPRI sales point price of produce (fresh fruit bunches). The total cost of production was calculated as:

$$X = a + b + c + d + e$$

Where variables a, b, c, d and e were: a: Cost of planting materials, b: Labour cost, c: Harvesting cost and e: Marketing cost.

The cost benefit ratio, which is the return per cash invested, was calculated by relating revenue generated to total cost of production or cash invested. This was obtained from the formula:

$$\text{Cost benefit ratio} = \frac{\text{Revenue generated}}{\text{Total cost of production}}$$

The income equivalent ratio was also calculated. This is the relative land area under which TSP was applied that is required to produce the incomes achieved in PR application. It was, therefore, extrapolated using the incomes of produce accrued from PR treatments, as the basis of comparism.

The establishment cost per hectare component of the production cost prior to imposition of treatments to plots was fixed for all the treatments involved.

3.14 STATISTICAL ANALYSIS

All data obtained, both from field and laboratory were subjected to analysis of variance (ANOVA) using Genstat statistical package (Genstat, 1997). Separation of means was done using the least significant difference at $P = 0.05$

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CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 GENERAL SOIL CHARACTERISTICS AND SOLUBILITY OF PHOSPHORUS FERTILIZER SOURCES

4.1.1 RESULTS

4.1.1.1 Soil characteristics

The results of physical and chemical analysis of the soil at the experimental site before imposition of treatments are presented in Table 3. The soil pH was extremely acid at both depths. Effective cation exchange capacity (ECEC), total nitrogen, organic matter content and exchangeable potassium were low and the level of available phosphorus was below the deficiency threshold for plants. Exchangeable Ca and Mg values were below the critical values of 5.0 and 1.0 cmol/kg respectively in both depths (Healed, 1965). Generally, the fertility of the soil was low and decreased with depth and response to the major nutrients especially P was expected.

From the results of particle size analysis, the content of sand, clay and silt were high, low and moderately low respectively at both depths. Hence, the soil was classified as sandy loam in both depths.

4.1.1.2 Solubility of phosphorus fertilizer sources

The solubility of the P sources is presented in Table 4. Neutral ammonium citrate (NH_4 citrate) and water were the extractants used for the P solubility test. Neutral ammonium citrate was more effective than water. Triple super phosphate (TSP) was more soluble in NH_4 citrate than the

Togo rock phosphate (TRP) by 88%. The total P content for TSP was 45% and this was about 43% more than total P content of TRP.

Table 3. Mean chemical and physical properties of soil at experimental site before application of treatments

Soil Property	Soil Depth (cm)	
	0-15	15-30
pH (1:2.5 H ₂ O)	4.42	4.13
Org. Carbon (%)	1.05	0.56
Organic matter (%)	1.81	0.97
Total N (%)	0.11	0.05
Avail. Bray's (mg/kg)		
P	0.80	0.20
K	69.20	131.30
Exchangeable bases (cmol/kg)		
Ca	2.88	1.44
Mg	1.60	0.64
K	0.06	0.07
Na	0.08	0.15
TEB	4.62	2.30
Exchangeable acidity (cmol/kg)	0.25	1.05
ECEC (cmol/kg)	4.87	3.35
Base saturation (%)	94.90	68.70
Particle size (%)		
Sand	68.00	60.00
Silt	27.00	32.00
Clay	5.00	8.00
Texture	Sandy loam	Sandy loam

Table 4. Total P and soluble P content of P sources

P source	Total P	NH ₄ citrate soluble P	Water soluble P
	<hr/> %		
Togo rock phosphate	25.50	2.17	0.20
Triple superphosphate	45.00	18.90	17.20

4.1.2 DISCUSSION

4.1.2.1 Soil characteristics

The low pH values of soil were similar to those reported for some Ghanaian soils by Adu and Tenadu (1979). Strong leaching of the basic cations out of the top soil contributed to low pH values. It is expected that this factor will affect the dynamics of all nutrients and especially phosphate because the available P depends to a large extent on interactions with constituents carrying a variable charge (Quang *et al.*, 1996).

The very low organic carbon content and low exchangeable bases particularly calcium reflected the generally highly weathered soils in the humid rainforest agro-ecological zone of the country (Owusu-Bennoah *et al.*, 2000). This property of the soil is attributed mainly to the excessive leaching of the soils caused by high rainfall associated with oil palm growing areas in Ghana and constant plant nutrient uptake by the crop. The low ECEC values could be attributed to the low organic matter and to the fact that the clay fraction is dominated by low activity clays (kaolinitic) (Owusu-Bennoah *et al.*, 1996). The high build up of available K in the 15-30 cm depth could be attributed to movement of K minerals due to leaching. The available P content of 0.8 and 0.2 mg/kg for the depths 0-15 and 15-30 cm depth respectively indicated that the soil was extremely low in P. According to Hartley (1988), the threshold deficiency for P is 10 mg/kg. This could be

attributed to the advanced stage of weathering of the parent rocks which lacked primary weatherable minerals necessary for nutrient recharge (Charreau, 1974).

Although all inorganic P cannot be considered sorbed P, these findings together with the Bray P results strongly suggested deficiency of P in the soil and hence, the need for P fertilizer application.

4.1.2.2 Solubility of phosphorus fertilizer sources

Phosphorus fertilizer dissolution is a reaction that occurs at the surface of the fertilizer particles (Barrow, 1990). Thus, super phosphate with a higher surface area dissolves better than rock phosphates. Ellis *et al.* (1955), working on solubility of rock phosphate confirmed this by observing higher solubility in superphosphates than in rock phosphates. Rock phosphate solubility is estimated as P dissolved by various extractants, because carbonate substitution is difficult to measure. According to the criteria proposed by Hammond *et al.* (1986), the solubility values in neutral ammonium citrate in this study placed TRP in a low solubility class. TRP is thus, normally amended with phosphate rock solubilizing materials such as compost, in order to enhance their solubility before being applied to crops (annuals and biannuals).

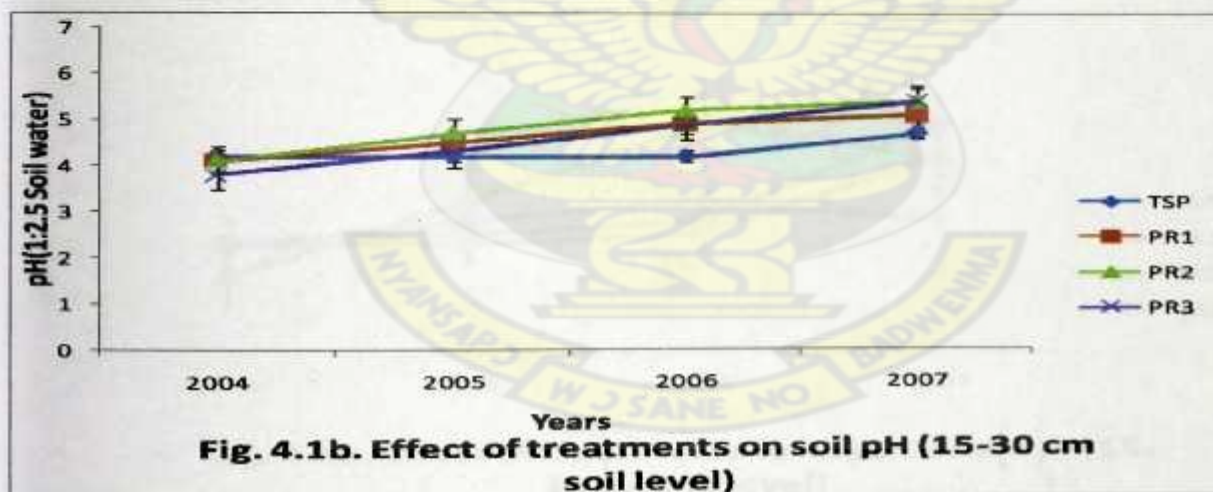
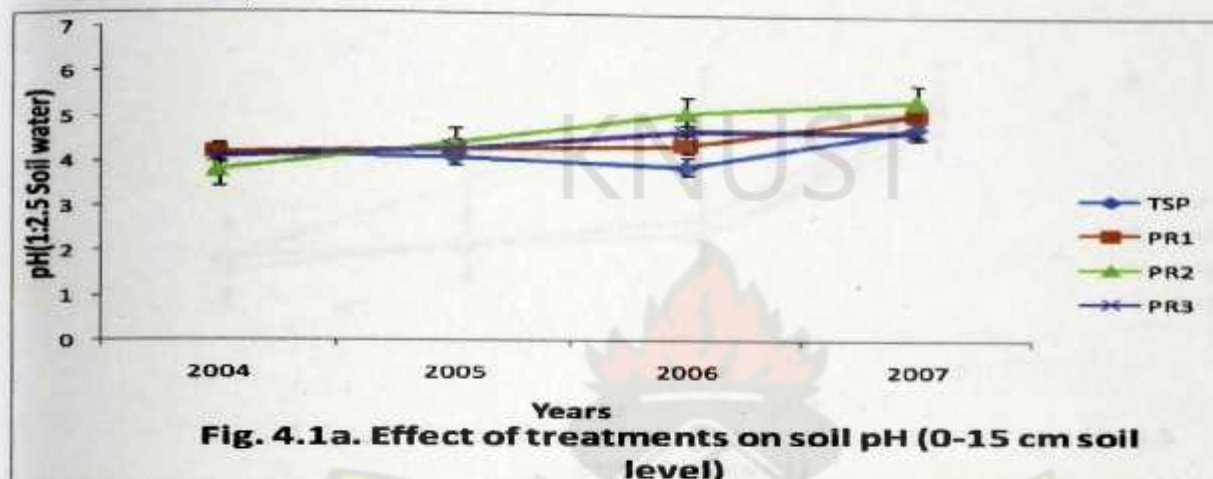
4.3 SOIL CHEMICAL FACTOR AND NUTRIENT DYNAMICS

4.3.1 RESULTS

4.3.1.1 Soil pH

The effect of treatments on soil pH is shown in Fig. 4.1a and Fig. 4.1b. Differences that were recorded during the test period were significant in 2004 and 2007 for both soil depths and 2006 in 0-15 cm soil depth only. Values of pH increased gradually from 2004 to 2007 for PR

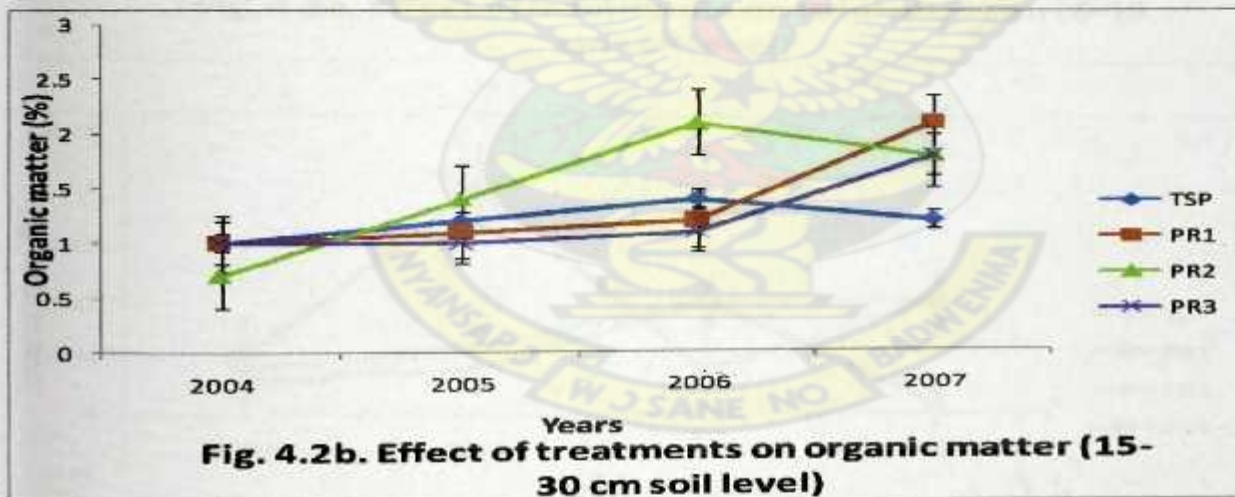
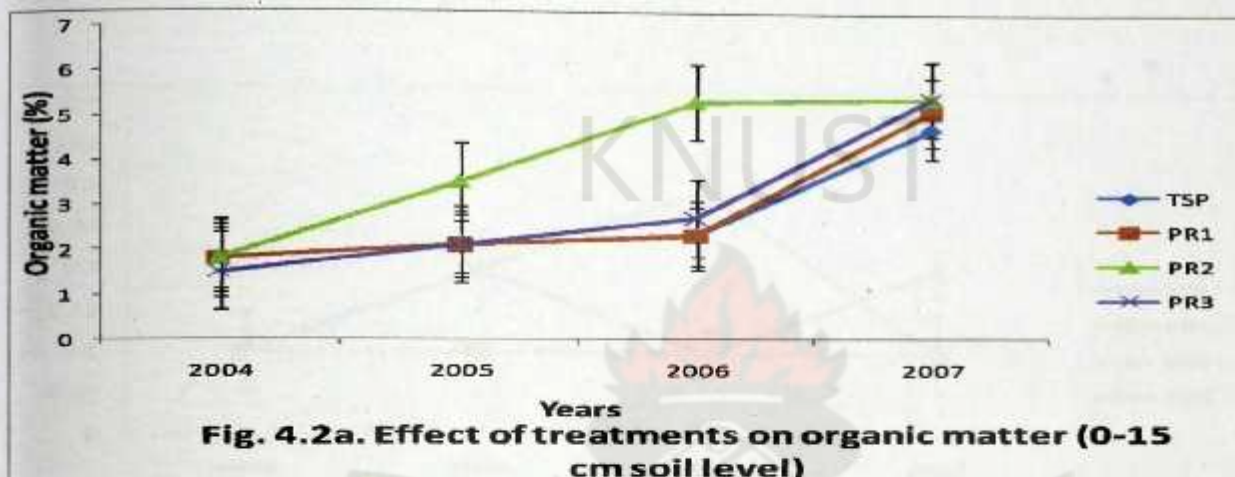
treatments in both soil depths. Soil pH values for the control (TSP) in soil depth 0-15 cm gradually decreased from 2004 to 2006 but eventually increased by 0.87 units from 2006 to 2007. Soil pH values for control (TSP) in 15-30 cm soil depth remained constant (4.22) from 2004 to 2006. However, there was an increase of 0.51 units from 2006 to 2007 in soil depth 15-30 cm.



4.3.1.2 Soil organic matter

Fig. 4.2a and Fig. 4.2b show organic matter content of the soil as affected by treatments. Changes in organic matter content over the test period were not significantly influenced in both soil depths. Significant difference was rather observed among treatments in 2004 at 15-30 cm

soil depth. Organic matter level were moderate to high and ranged from 1.56 to 5.33 % in the 0-15 cm. These values decreased with soil depth. A gradual increase in organic matter content from 2004 to 2007 during the period was recorded. However, from 2006 to 2007 in the PR2 treatments, both soil depths experienced organic matter reduction by 4.00 % and 15.00 % for 0-15cm and 15-30 cm respectively.

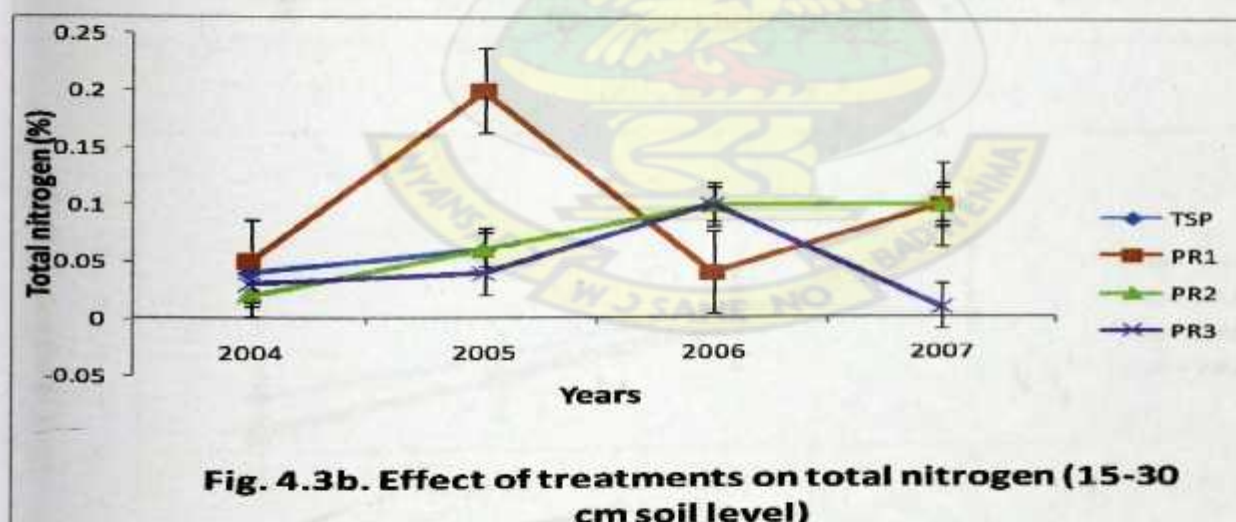
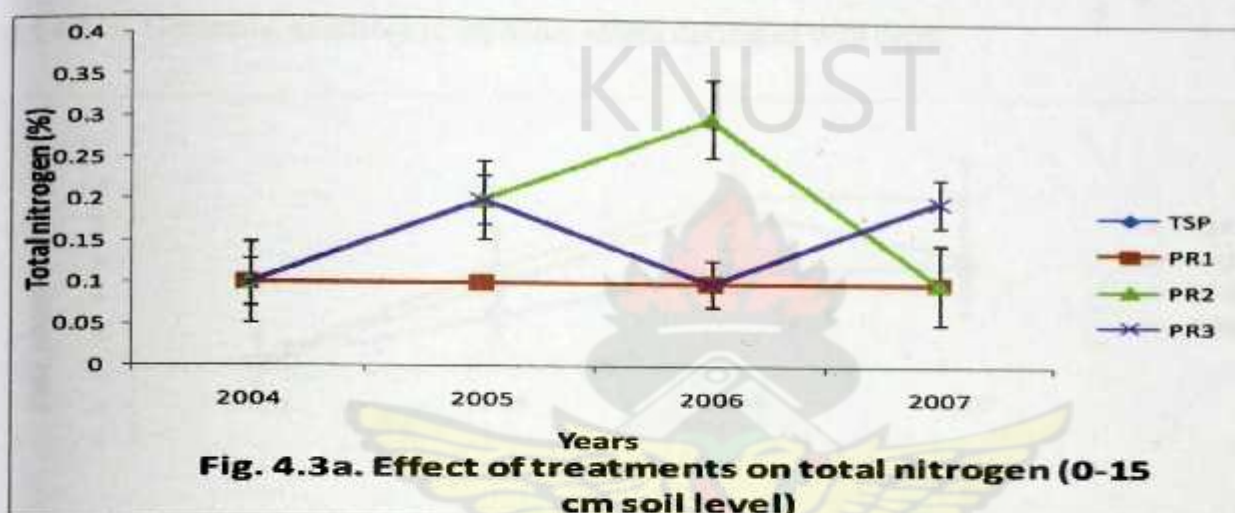


4.3.1.3 Total nitrogen

Total nitrogen values showed no significant difference among treatments for both soil depths (Fig. 4.3a and Fig. 4.3b). Comparatively, total N values in 2004 were lower than 2007 values.

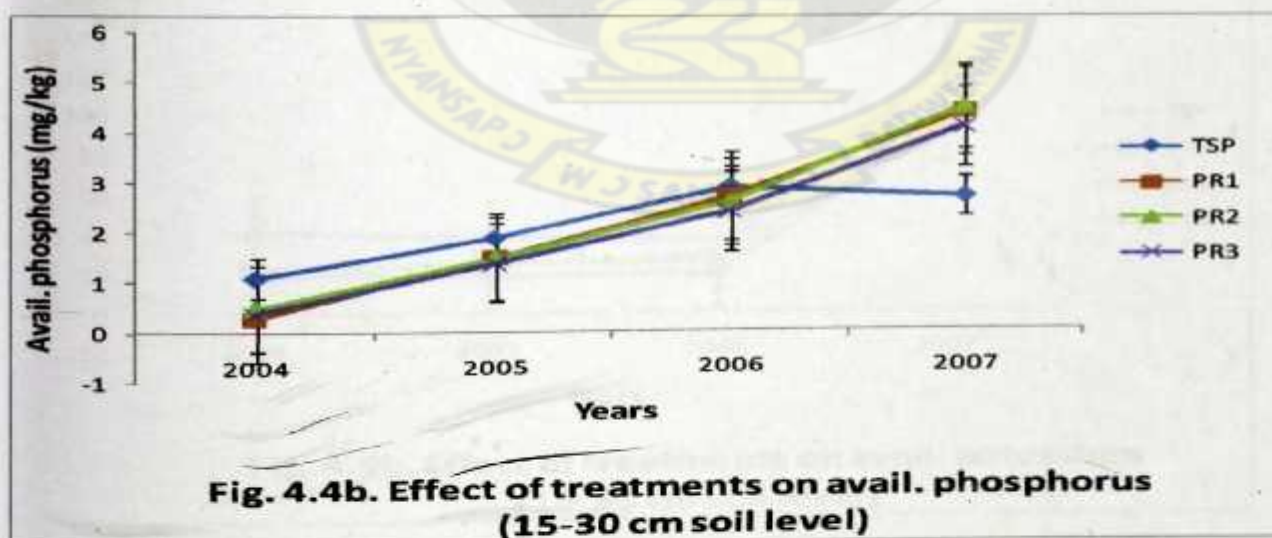
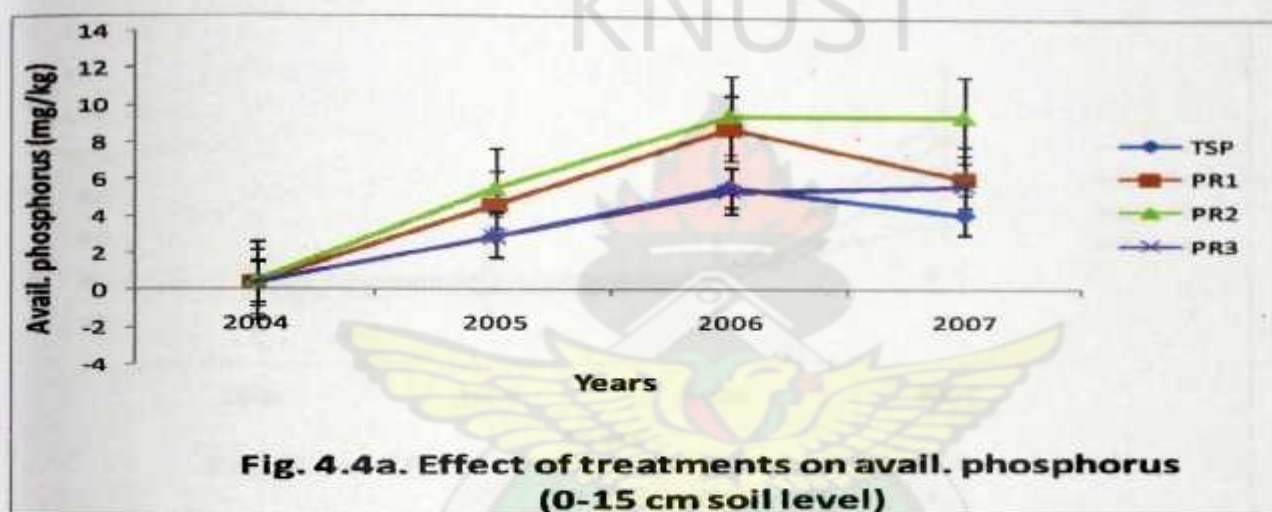
Increase in total N values in 2007 over 2004 were 28.0 and 51.0 % for 0-15 cm and 15-30 cm soil depths respectively. Values recorded in 2005 and 2006 for PR2 treatment in 0-15 cm soil depth had the

highest total N values and these were higher than the critical soil nutrient value of 0.2% (Hartley, 1988). However, by 2007 PR2 treatment in soil depth 0-15 cm had dropped by 20.0 %.



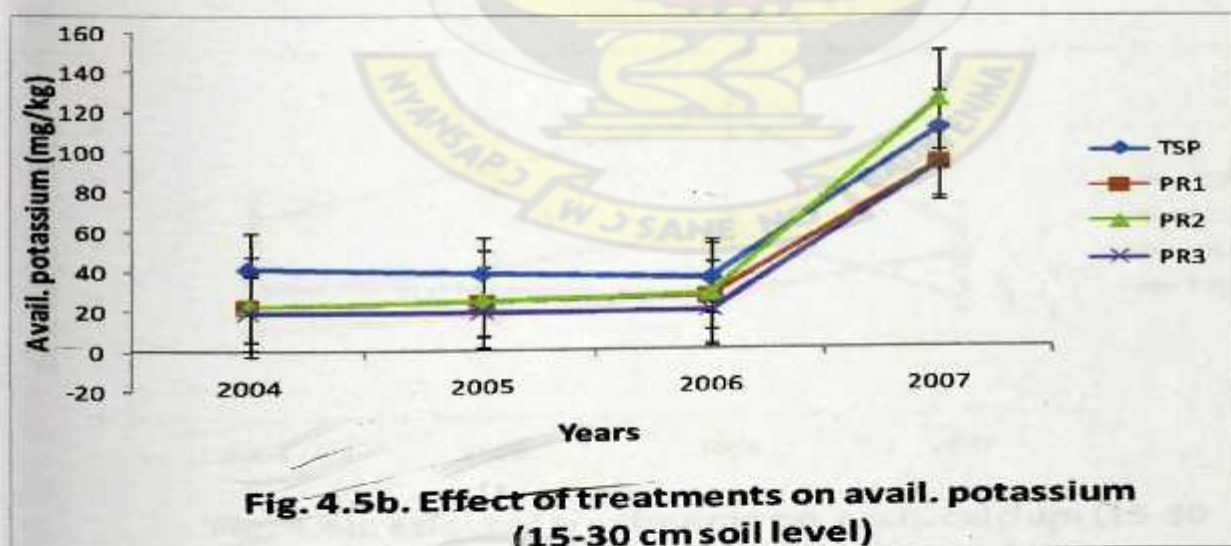
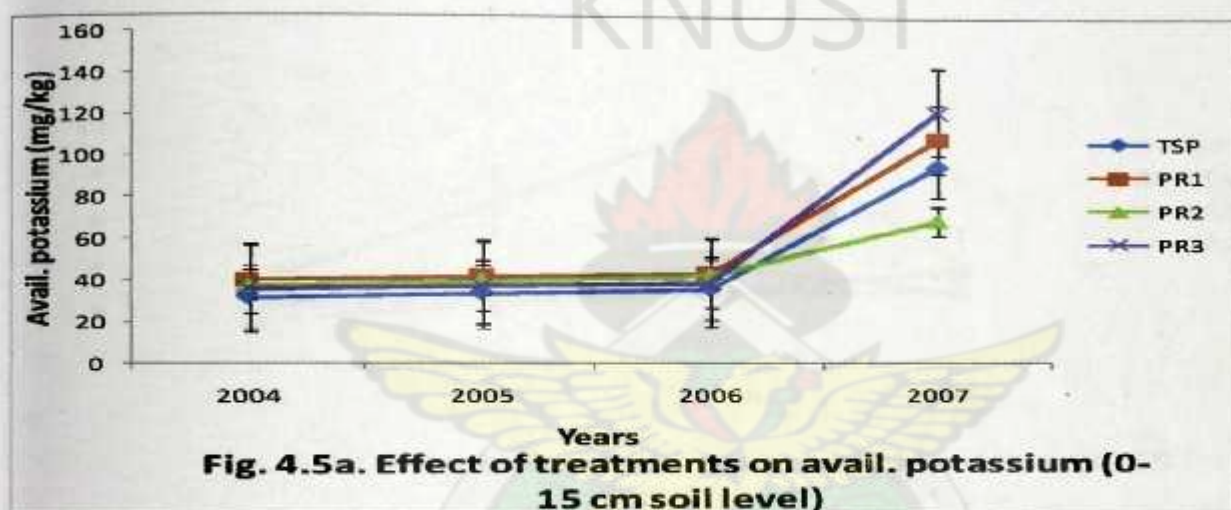
4.3.1.4 Available phosphorus

Fig. 4.4a and Fig.4.4b show the available phosphorus levels as influenced by treatments. Differences that were recorded during the period were not significant in both soil depths. Available phosphorus values increased gradually from 2004 to 2006. However, from 2006 to 2007 there was a drop in available phosphorus values for treatments TSP (control) in 0-15 cm, PR1 in 0-15 cm and TSP (control) in 15-30 cm soil depth. The respective drops were 26.0, 31.6 and 6.5 %. Generally, available phosphorus values decreased with depth.



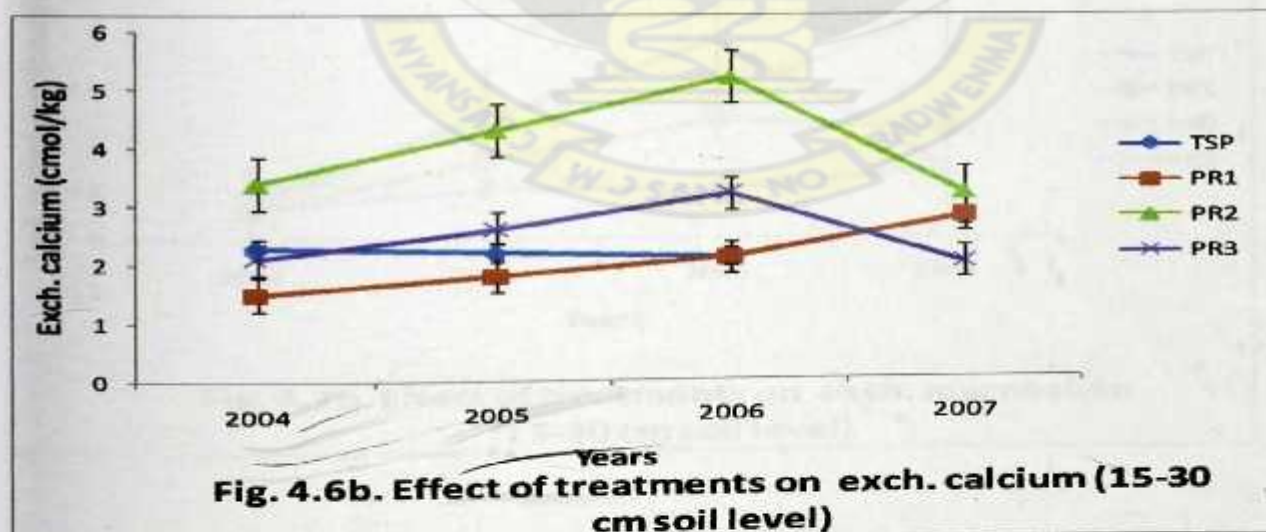
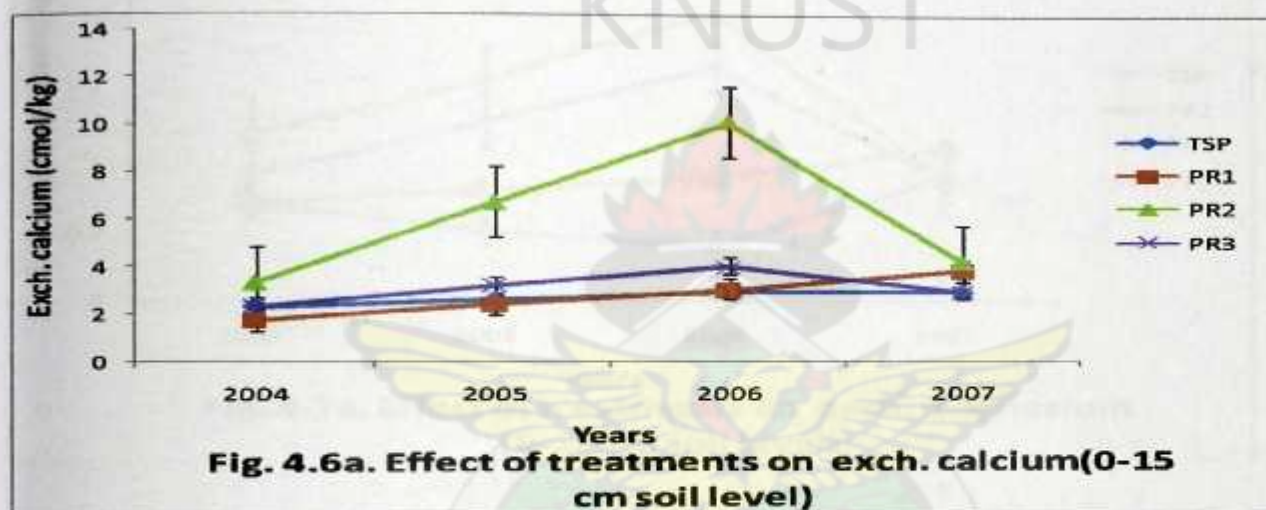
4.3.1.5 Available potassium

Available potassium as influenced by treatments is shown in Fig. 4.5a and Fig. 4.5b. There was a gradual increase in available potassium from 2004 to 2007 for all treatments in both depths. Available potassium values were generally low to high and ranged from 31.50 to 121.60 mg/kg and 19.50 to 125.6 mg/kg in the 0-15 cm and 15-30 cm depths respectively. However, increased values from 2006 to 2007 were more pronounced. Treatment differences that were recorded during the test period were not significant in both soil depths.



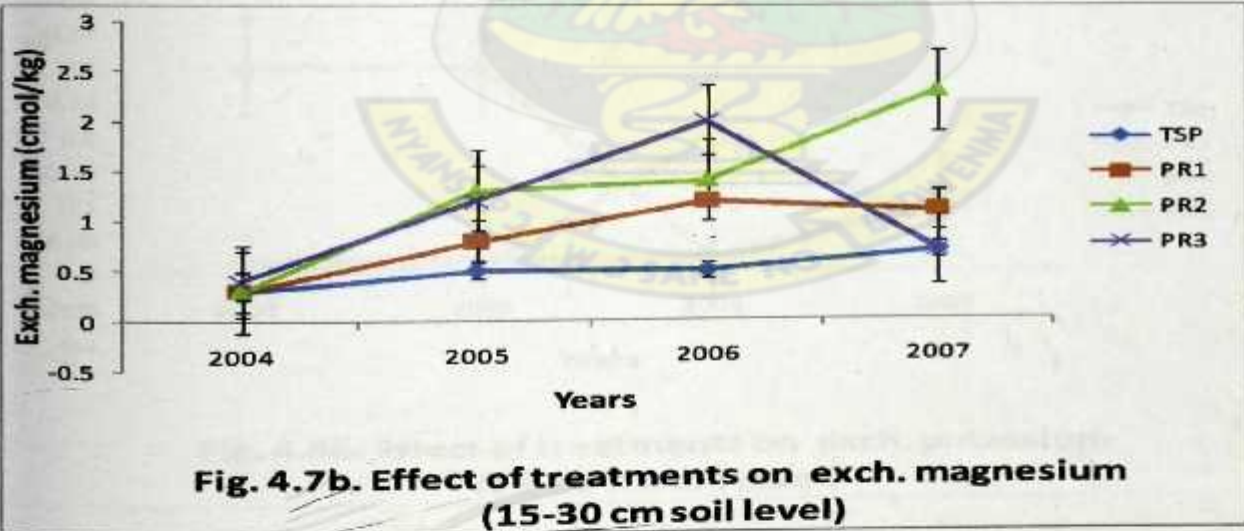
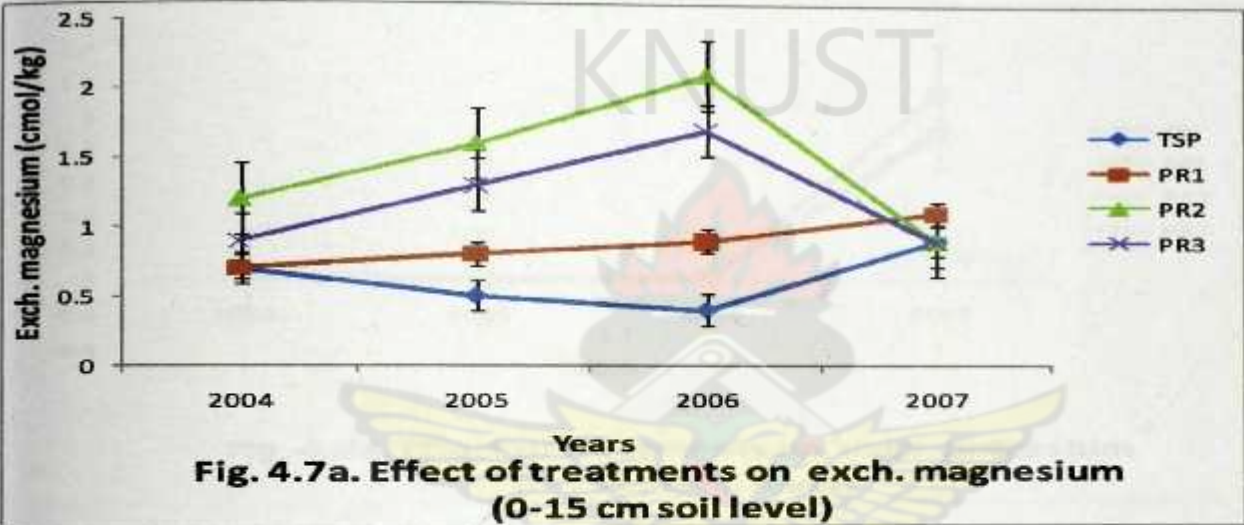
4.3.1.6 Exchangeable calcium

Fig. 4.6a and Fig.6b show the effect of treatments on the dynamics of exchangeable calcium. Values of exchangeable calcium increased from 2004 to 2007. However, from 2006 to 2007 a drop in values were recorded in treatments PR2 and PR3 in both soil depths. The drop from 2006 to 2007 in 0-15 cm soil depth for treatments PR2 and PR3 were 58.1 % and 33.0 % respectively. The drop in exchangeable calcium from 2006 to 2007 in 15-30 cm soil depth was about 38 % and 39 % for treatments PR2 and PR3 respectively.



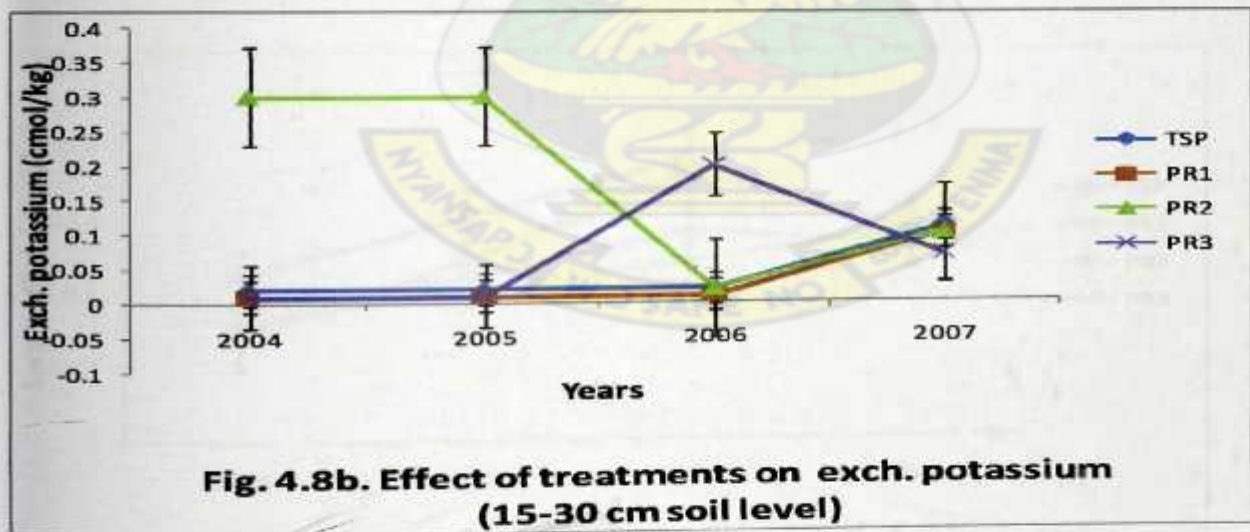
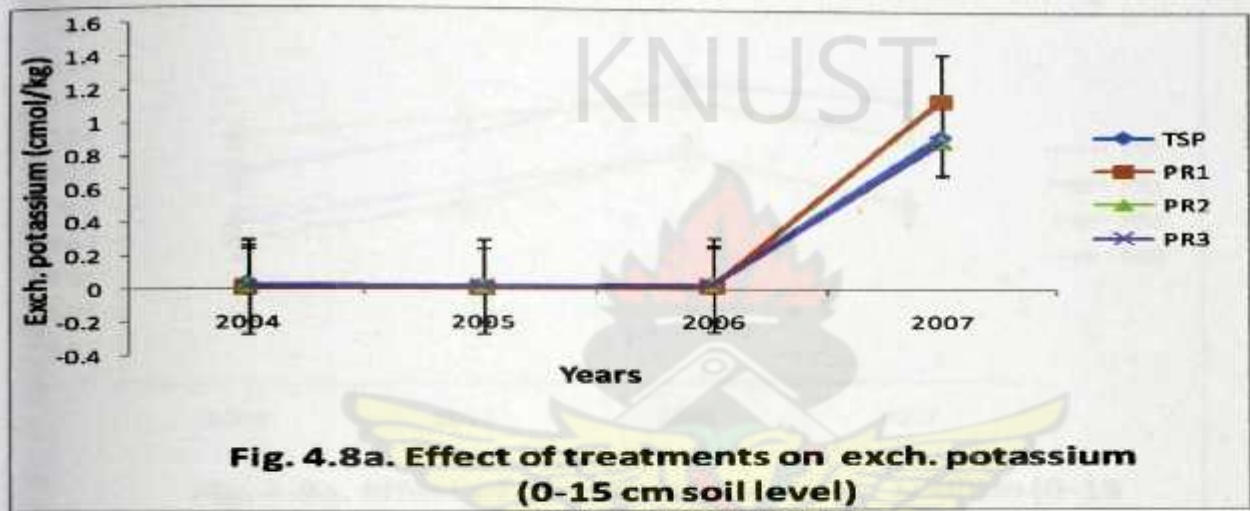
4.3.1.7 Exchangeable magnesium

Exchangeable magnesium as influenced by treatments is shown in Fig. 4.7a and Fig. 4.7b. Values increased gradually from 2004 to 2007 in 0-15 cm depth for TSP and PR1. Treatments PR2 and PR3 dropped from 2006 to 2007 by 1.1 and 0.8 units respectively. For 15-30 cm depth, a drop in values from 2006 to 2007 were 15.8 and 168 % respectively for PR1 and PR3.



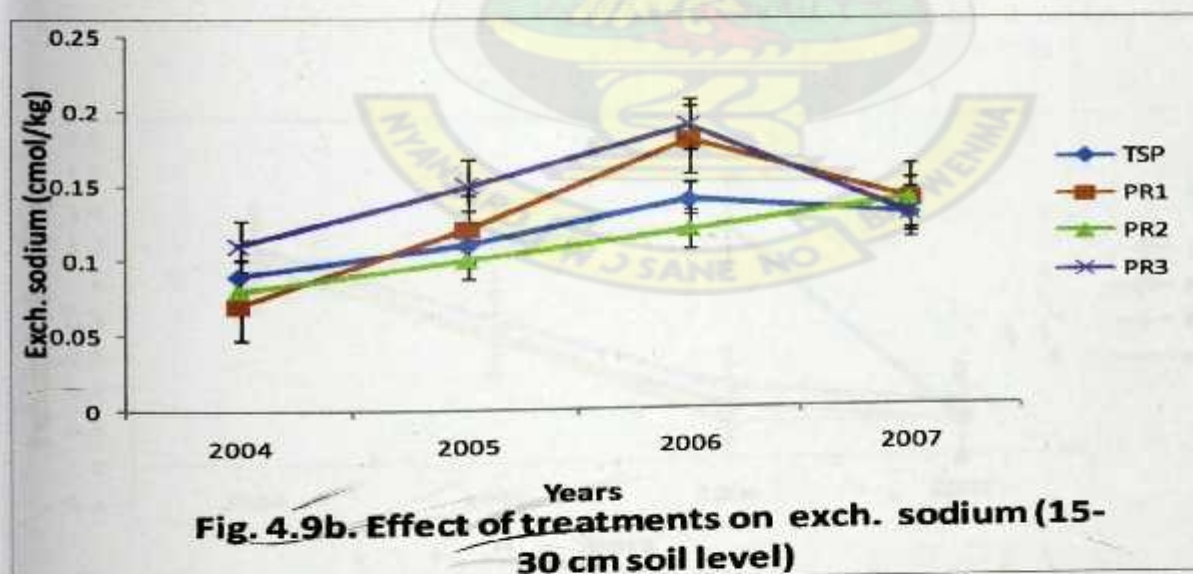
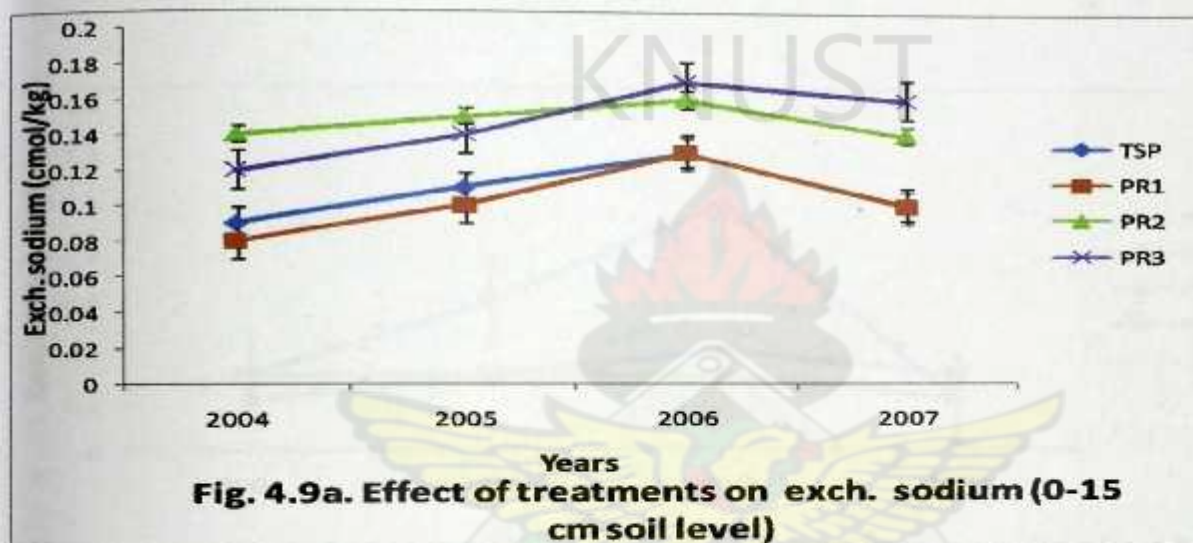
4.3.1.8 Exchangeable potassium

More than 80 % of values recorded were below the deficiency threshold of 0.15 cmol/kg (IRHO, 1960) by 2006 (Fig. 4.8a and Fig. 4.8b). There were fluctuations in the values of exchangeable potassium from 2004 to 2007 in the 15-30 cm depth. However, values increased gradually from 2004 to 2007 in the 0-15 cm soil depth.



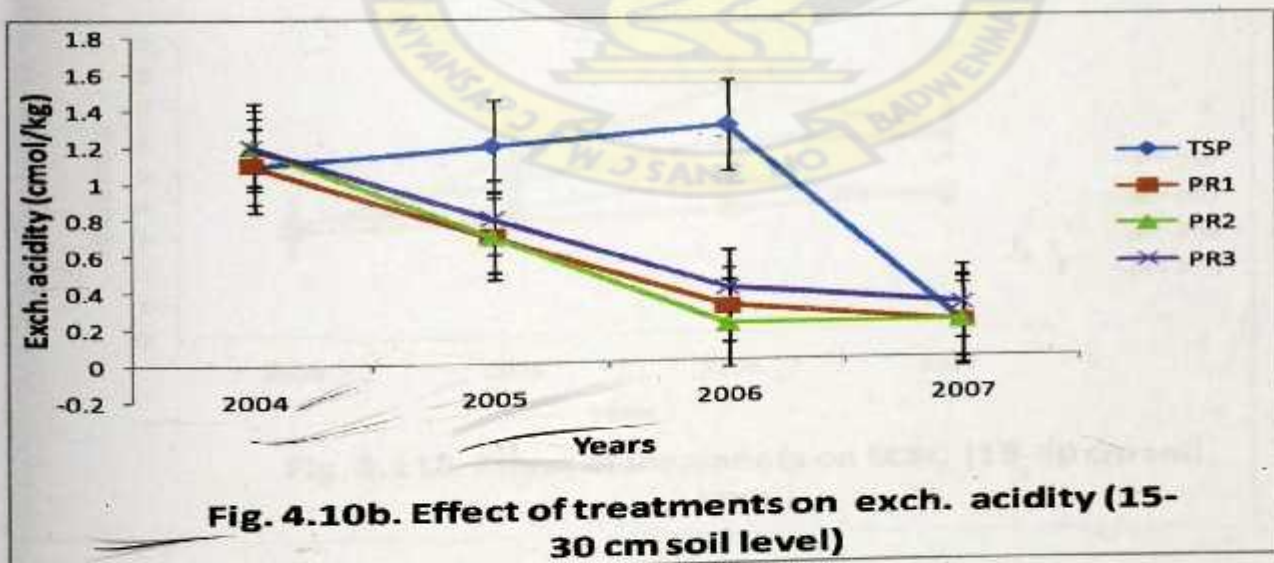
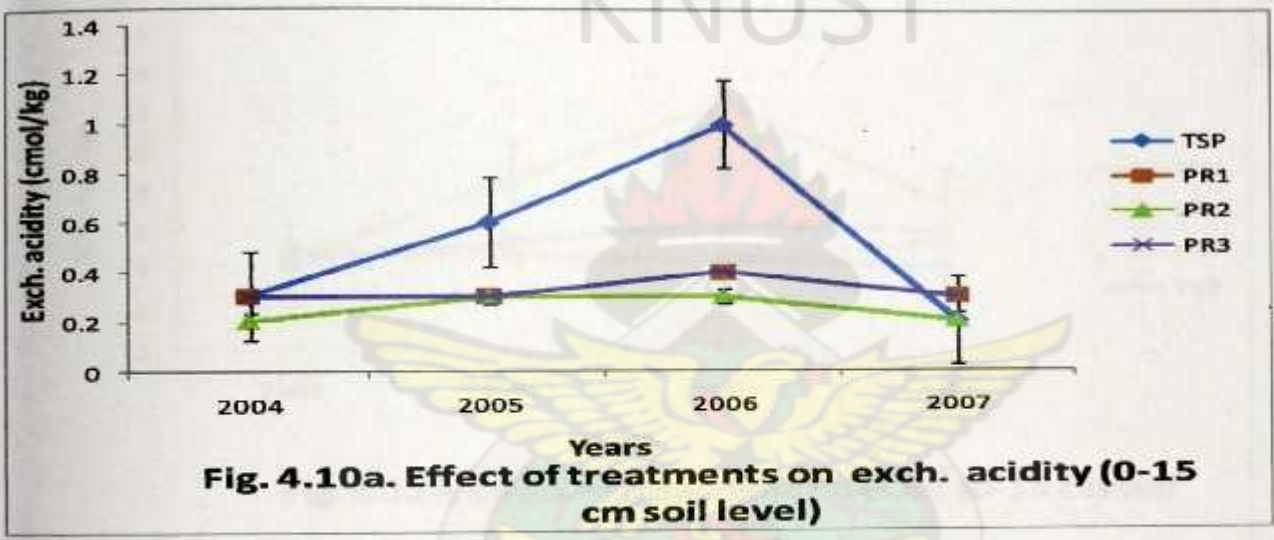
4.3.1.9 Exchangeable sodium

Exchangeable sodium as influenced by treatments is shown in Fig. 4.9a and Fig. 4.9b. Differences were not significant in both depths. Values of exchangeable sodium increased gradually from 2004 to 2006 and dropped in 2007. The mean drop from 2006 to 2007 were 15 % and 14 % for the 0-15 cm and 15-30 cm soil depths respectively.



4.3.1.10 Soil exchangeable acidity

Table 14 shows soil exchangeable acidity as influenced by treatments. Differences that were recorded during the test period were not significant in both soil depths. Soil exchangeable acidity values ranged from 0.20 to 1.07 cmol/kg and 0.18 to 1.35 cmol/kg for 0-15 cm and 15-30 cm soil depth respectively. Values that were recorded in 2004 for both soil depths were higher than values obtained at the end of the study (2007).



4.3.1.11 Effective Cation Exchange Capacity (ECEC)

Fig. 4.11a and Fig. 4.11b show effective cation exchange capacity (ECEC) as influenced by treatments. Values of ECEC decreased with depth. The highest ECEC of 12.6 cmol/kg occurred in PR2 at a depth 0-15 cm in the year 2006 with the lowest of 3.23 cmol/kg recorded by PR1 in 2004 at a depth of 0-15 cm. A gradual decrease in ECEC from 2004 to 2007 in the 0-15 cm for TSP treatment (control) was recorded. By the end of the study individual PR treatments recorded higher values than TSP (control) in both soil depths.

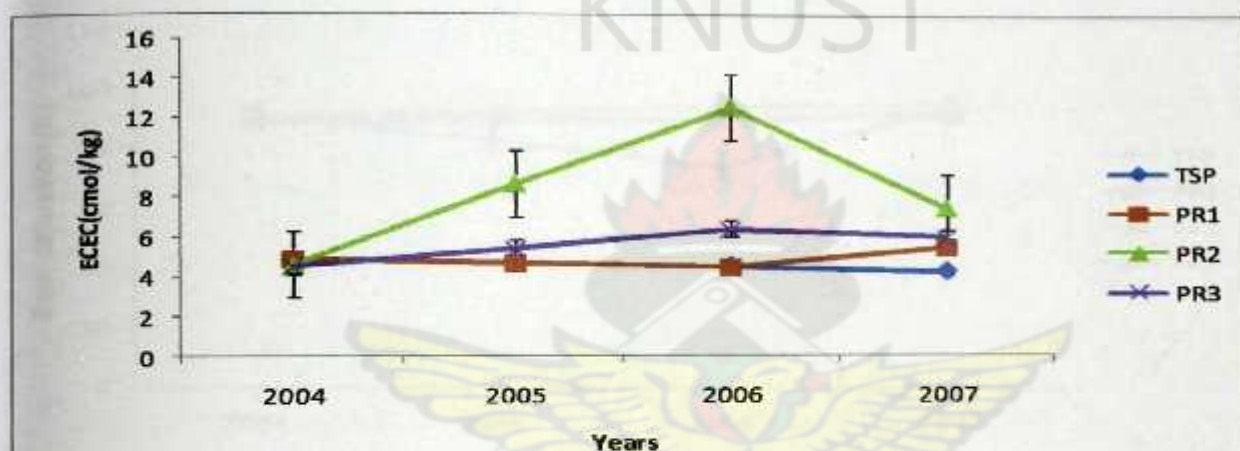


Fig. 4.11a. Effect of treatments on ECEC (0-15 cm soil level)

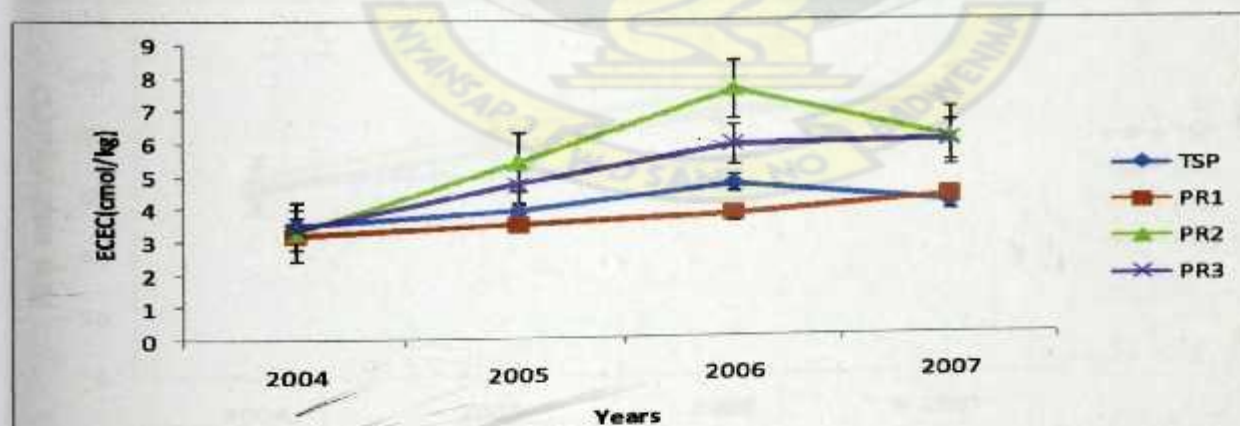
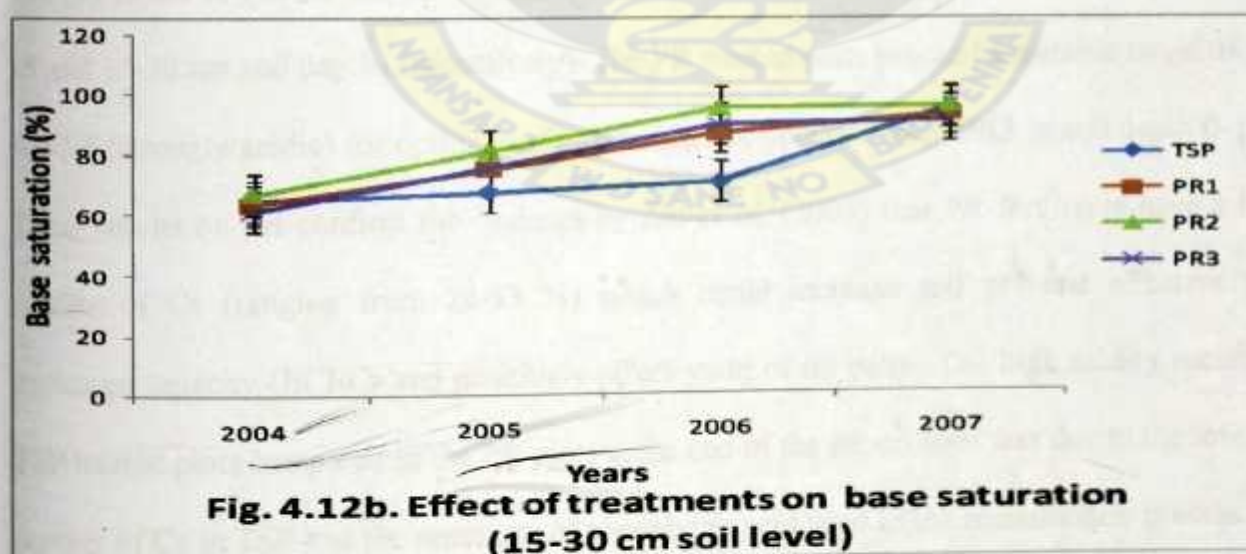
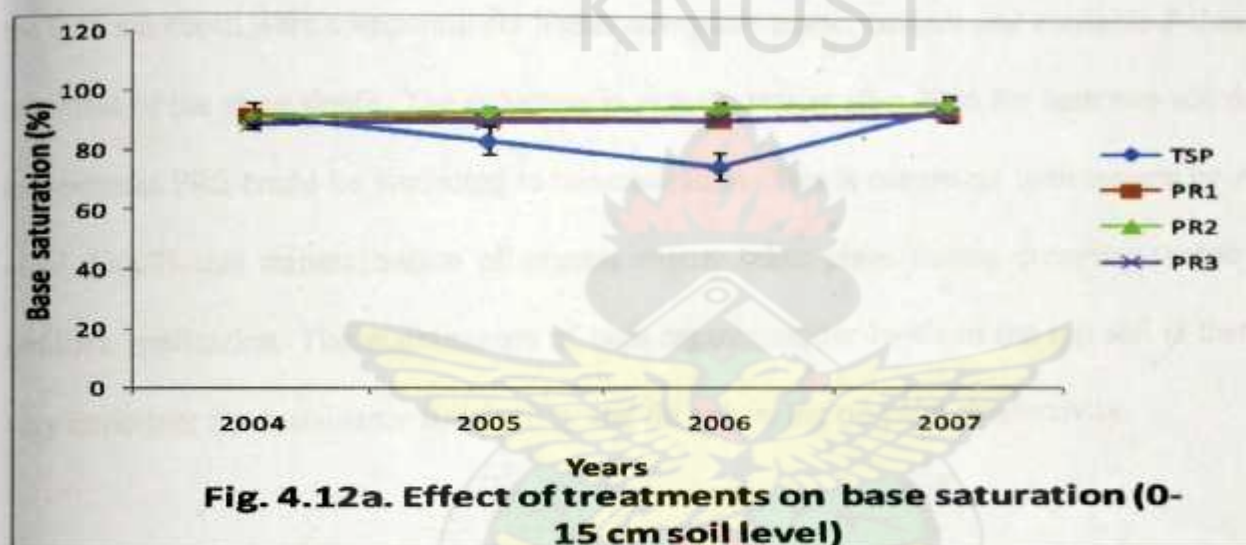


Fig. 4.11b. Effect of treatments on ECEC (15-30 cm soil level)

4.3.1.12 Percent base saturation

Values of base saturation during the study period generally decreased with depth. Base saturation levels were moderate to high and ranged from 75.00 to 96.86 % and 61.43 to 96.17 % in the 0-15 cm and 15-30 cm respectively (Fig. 4.12a Fig. 4.12b). There was a gradual increase in base saturation levels from 2004 to 2007 except treatments TSP and PR1 in the 0-15 cm soil depth which recorded fluctuations in values. Treatment effects were not significantly different in the 0-15 cm depth, but in the 15-30 cm, significant differences were recorded in 2004 and 2007.



4.3.2 DISCUSSION

Soil nutrient dynamics

Soil nutrients were concentrated in the top 0-15 cm and tended to decrease with depth, suggesting that a greater part of these nutrients may be associated with organic matter present in the top soil (Aweto, 1988). While superphosphate application generally leads to a reduction of soil organic matter in the top soil, PR applied with other inorganic fertilizers resulted in significant increases in total organic C, available-P, soil respiration, microbial biomass and enzyme activities Melero *et al.* (2006). The results of this study showed that, PR treatments in the 0-15 cm depth were comparatively higher in organic matter content and available-P than TSP treatment of the same depth. The reduction in organic matter after 2006 for both two soil depths in treatment PR2 could be attributed to mineralization. This is consistent with reports by Azeez *et al.* (2007) that mineralization of organic matter takes place during cropping season after fertilizer application. The maintenance of high organic matter levels in the top soil is therefore very important for sustainable soil fertility and for enhancing oil palm productivity.

The pH of the soil at the start of the experiment was extremely acid (pH 4.42 and 4.13 for the 0-15 and 15-30 cm soil depths respectively). The PR treated plots reached a suitable range of pH of 5.0-5.5 (strongly acidic) for optimum oil palm nutrient uptake except PR3 in soil depth 0-15 cm. These results on pH confirm the findings by Zin *et al.* (2005) that PR fertilizers have a higher content of Ca (ranging from 24-33 %) which could increase soil pH and effective cation exchange capacity (ECEC) and positively affect yield of oil palm. The high acidity recorded in TSP treated plots compared to the PR plots at the end of the experiment was due to the low content of Ca in TSP and the remnants of phosphoric acid used in the manufacture process of the triple superphosphate fertilizers.

The available P (Bray P) at the start of the experiment was low and compares with that reported by Ankomah *et al.* (1995) in similar Ghanaian soils. Thomas and Peaslea (1973) suggested that most soils containing extractable P of less than 15 mg/kg as determined by Bray 1 method could be defined as being deficient in available P for optimal plant growth. These are similar to the values suggested by Olson and Engelsted (1972) and Menon *et al.* (1995). By the end of the experiment the highest available P was still below the medium range of 10-20 mg/kg (Hartley, 1988). The results obtained for this study confirmed the findings of Pieri (1986) that P is one of the most limiting nutrients for crop growth in tropical soils. Available P reported in PR treated plots were promising than values obtained for TSP treated plots. According to Sale and Mokwunye (1993), PR applied to P-deficient acid soils encountered in humid forest zone dissolve slowly to sustain soil levels and plant growth. Allen *et al.* (1995) also observed slow release of P to the soil by PR. As a result, Adam *et al.* (1987) suggested that PR should be used on perennial crops rather than annual crops and research must focus on treating PR to increase solubility. Studies by Hammond *et al.* (1986) and Chien and Menon (1995) have shown that partial acidulation of PR (PAPR) is one way to increase water solubility and agronomic effectiveness of PRs at a lower cost than would be required to manufacture the conventional, fully acidulated fertilizers as SSP or TSP. The low P values recorded in the 15-30 cm could possibly be due to P-fixation by aluminisilicates, since clay generally accumulates in the subsoil of tropical soils (Obeng, 1990).

The status of N was relatively low, both at the beginning and at the end of the study as well. Values of N decreased with depth and almost all the N values recorded were below the medium

range of 0.1-0.2 % (Hartley, 1988). Continual supply of N is necessary since it is very difficult to build large N reserves.

Lower soil P levels as experienced in this study, could prevent the uptake and the use of available potassium (Hartley, 1988). This and the fact that K was applied annually might have given rise to the general increase in available K as experienced from 2006 to 2007 in this study. This could also be due to the replenishment from the potassium pool at the end of the experiment. The build up of available K in the 15-30 cm soil depth in 2007 may indicate the movement of K fertilizers due to leaching. This observation supports that of Weerasinghe and Premalal (2002) who observed a build up of K in deeper soil layers indicating the movement of K fertilizers due to leaching.

The low pH in TSP treated plots resulted in a smaller proportion of exchangeable Ca and Mg (Roy *et al.*, 2006). According to Havlin *et al.* (1999), the availability of K^+ is generally dependent on its concentration relative to that of Ca^{2+} and Mg^{2+} . Thus, K^+ uptake increases as concentrations of Ca^{2+} and Mg^{2+} decline in the soil solution and vice versa. This may explain the yearly variation in almost all the soil nutrients analyzed.

In a study of soil nutrient dynamics, Roy *et al.* (2006) observed that the content of available nutrients and their degree of availability and accessibility was not a static condition but an ever-changing and very dynamic process due to the various inorganic and biochemical processes that take place in soils.

4.4 SOIL MICROBIAL CARBON, NITROGEN AND PHOSPHORUS

4.4.1 RESULTS

Microbial C

Microbial C increased in all treatments during the four year study period (Fig. 4.13). The increases were 60, 30, 75 and 50 % in soils treated with TSP (control), PR1, PR2 and PR3 respectively.

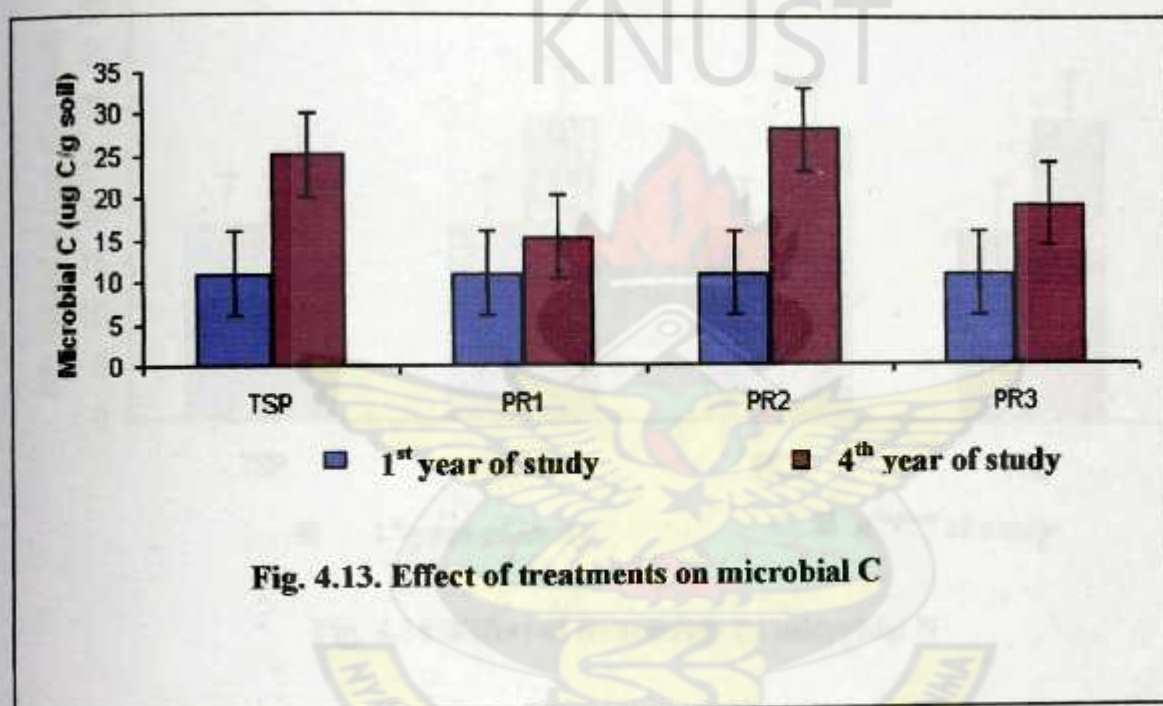
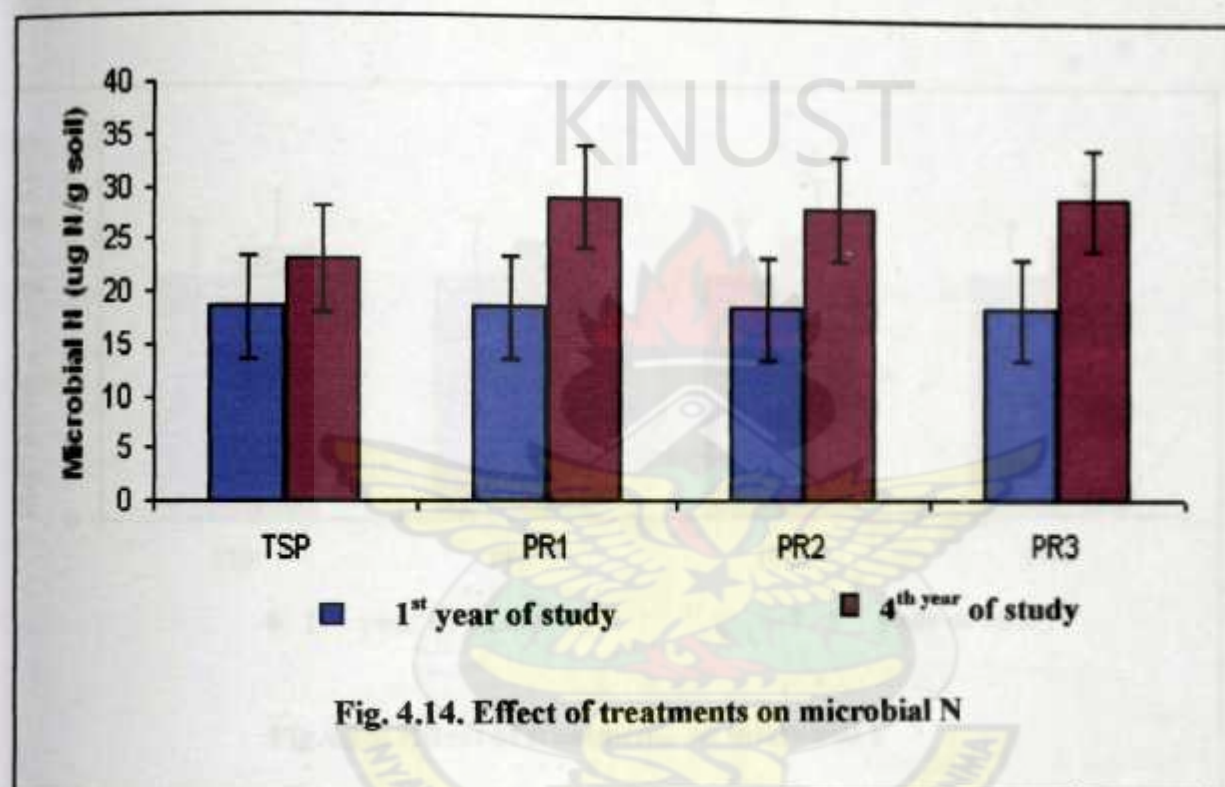


Fig. 4.13. Effect of treatments on microbial C

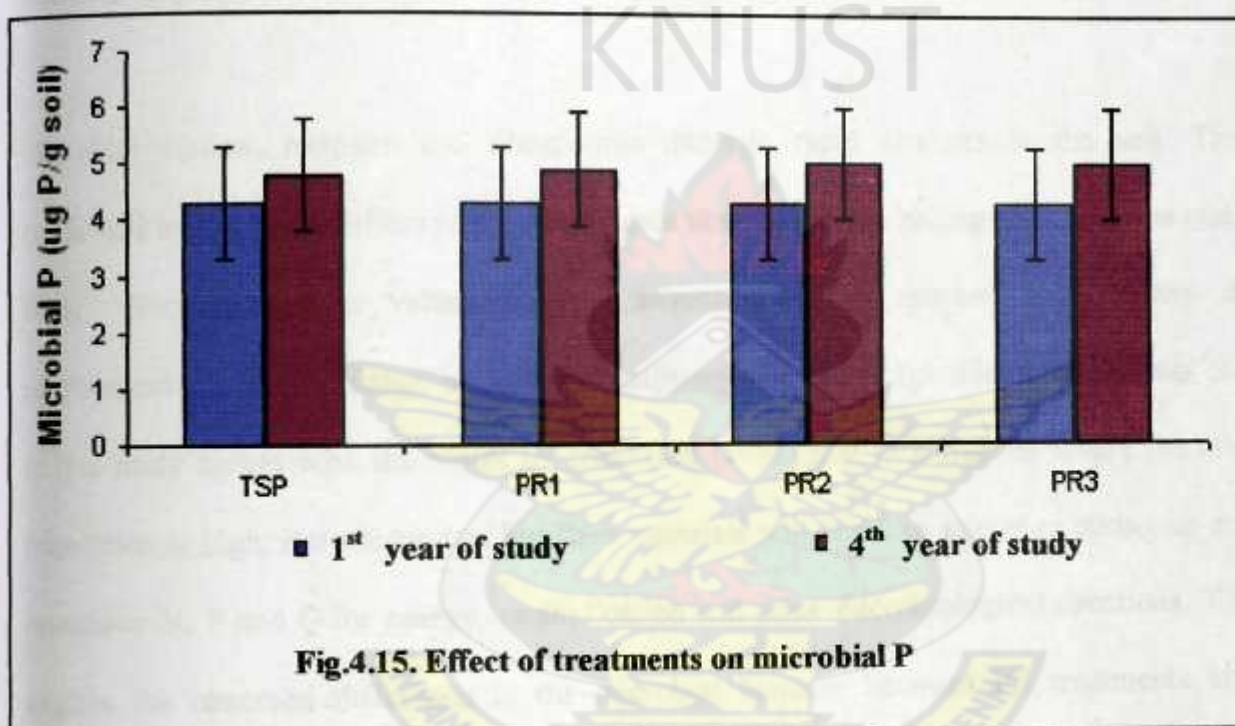
Microbial N

Microbial N increased in value by 20 % in plots that were treated with TSP (control) at the end of the study. Increases in values were 45, 40 and 46 % for PR1, PR2 and PR3 treatments respectively (Fig.4.14). No significant difference occurred among the treatments ($P>0.05$).



Microbial P

There were marginal increases in microbial P values (Fig. 4.15) as compared to microbial C and N. Increase in values for microbial P from 1st year to 4th year of study for TSP, PR1, PR2 and PR3 were 0.4, 0.5, 0.7 and 0.7 $\mu\text{gP/g}$. No significant differences were recorded among treatments ($P>0.05$).



4.4.2 DISCUSSION

Treatments that were applied to oil palm in this study influenced soil microbial biomass. Due to its dominant contribution in soil metabolism, as well as importance as a sink and source of nutrition for plants, microbial biomass is considered to be one of the main determinants of soil fertility (Jenkinson and Ladd, 1981; Mc Gill *et al.*, 1986). It contributes to the improvement of soil productivity through continuous immobilization and release of nutrients, preventing them from being lost through leaching and volatilization. The immobilized nutrients are later made available to the plants.

Microbial carbon, nitrogen and phosphorus undergo rapid changes in the soil. This was confirmed by the great differences between data obtained at the beginning and at the end of the study. The increase in values implied increases in the number and activity of soil microorganisms such as fungi, bacteria and actinomycetes. The high microbial biomass observed in this study agrees with the report by Jenkinson (1981) that in situations where the microbial population is high, introduction of fertilizer materials will result in microbes taking up nutrients especially N, P and C for energy, multiplication and other microbiological functions. This may explain the observed difference in the microbial biomass between PR treatments and TSP treatment (control). Soil microbial biomass is a very important reservoir of phosphorus in the soil (Oberson *et al.*, 1997). Considering the microbial P values at the end of the four year period, addition of phosphorus resulted in more phosphorus being taken up by microbes. This high demand for P by microbes implied that a greater amount of phosphorus was held by microbes and less P adsorbed by the highly reactive surfaces of Al and Fe Oxides and hydroxides in the tropical soils. Microbial population plays a central role in P cycling and availability (Morel *et al.*, 1997).

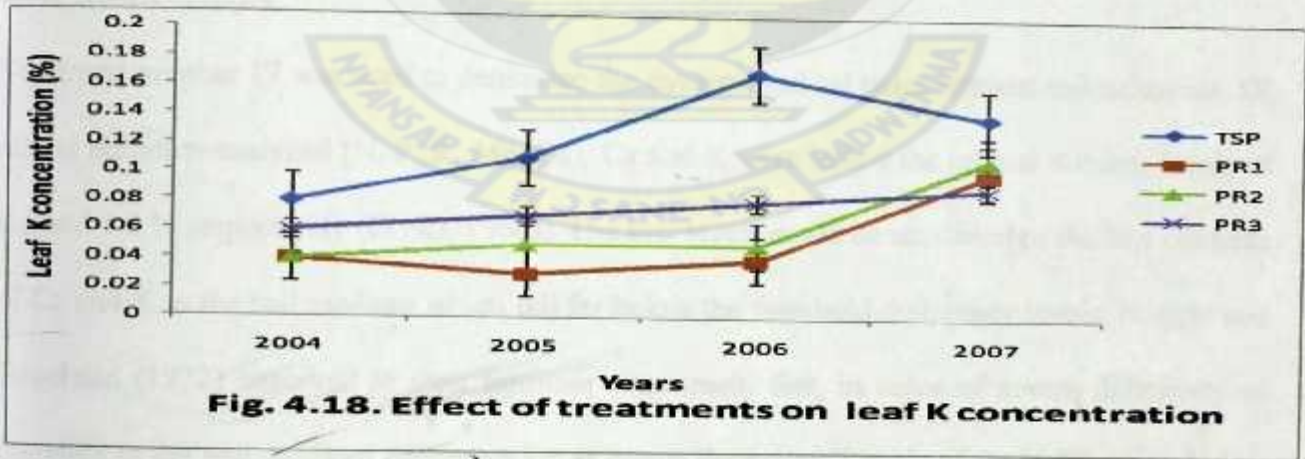
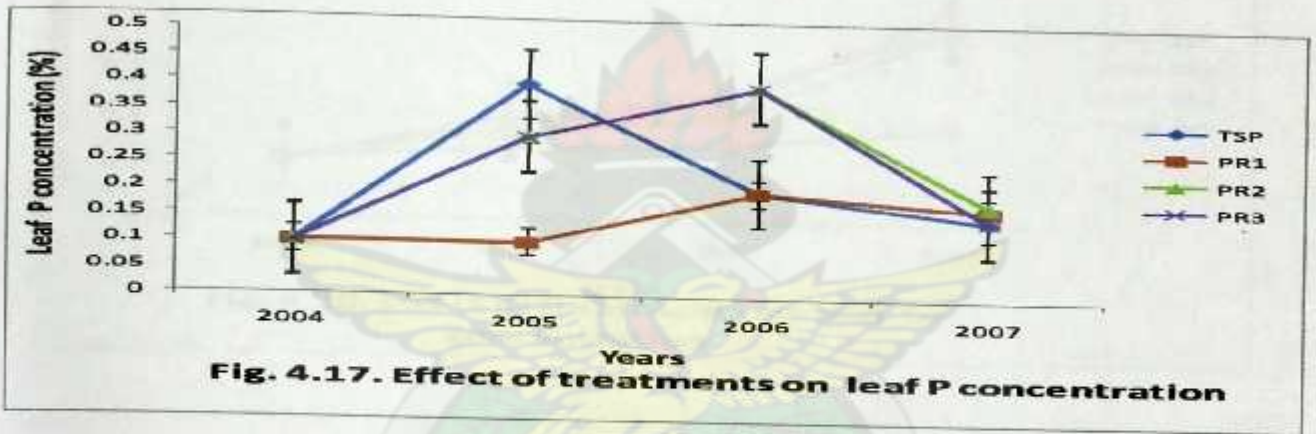
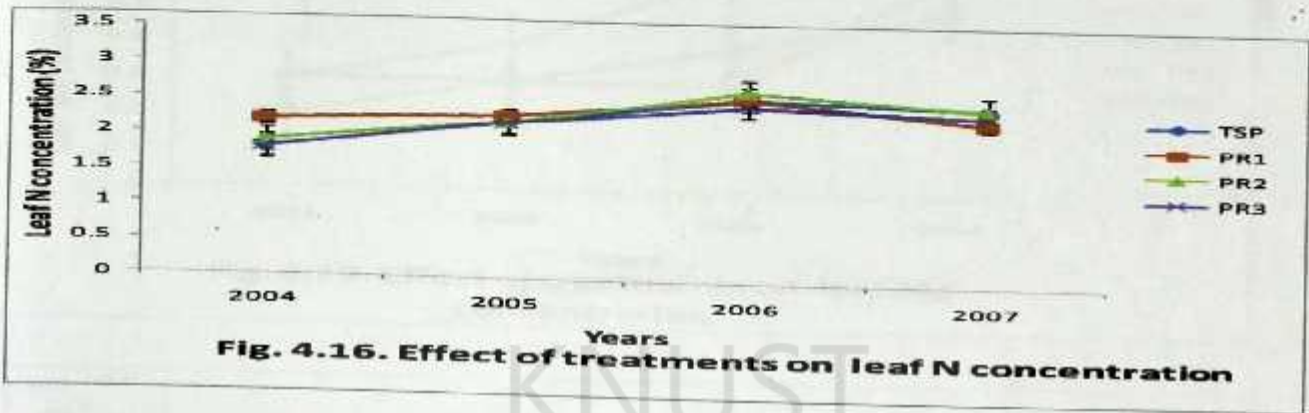
Generally, observed microbial values were greater in PR treated plots than TSP plots. This could be attributed to slightly acid pH values observed in PR treated plots. This was confirmed by Duponnois *et al.* (2005). In their study they postulated that application of PR enhanced microbial biomass C, N and P mineralization. Soil test phosphorus level below 10.0 mg/kg soil was recorded at the end of the study. From this study, it can be deduced that if the microbes hold more P, then soil management practices should be geared towards making optimum use of microbial P. This will improve soil productivity and enhance synchronization of P release by microbes and P demand by the crop.

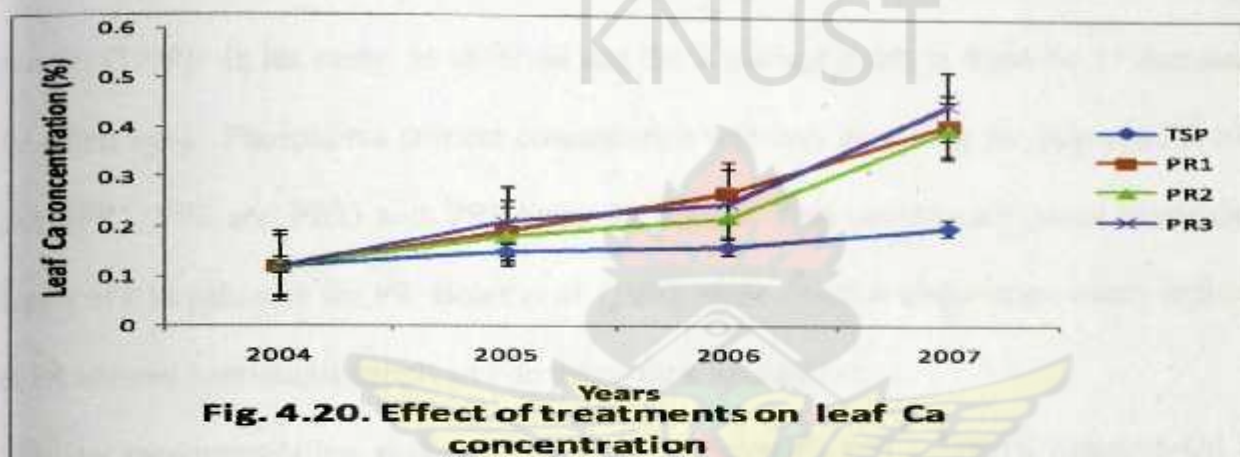
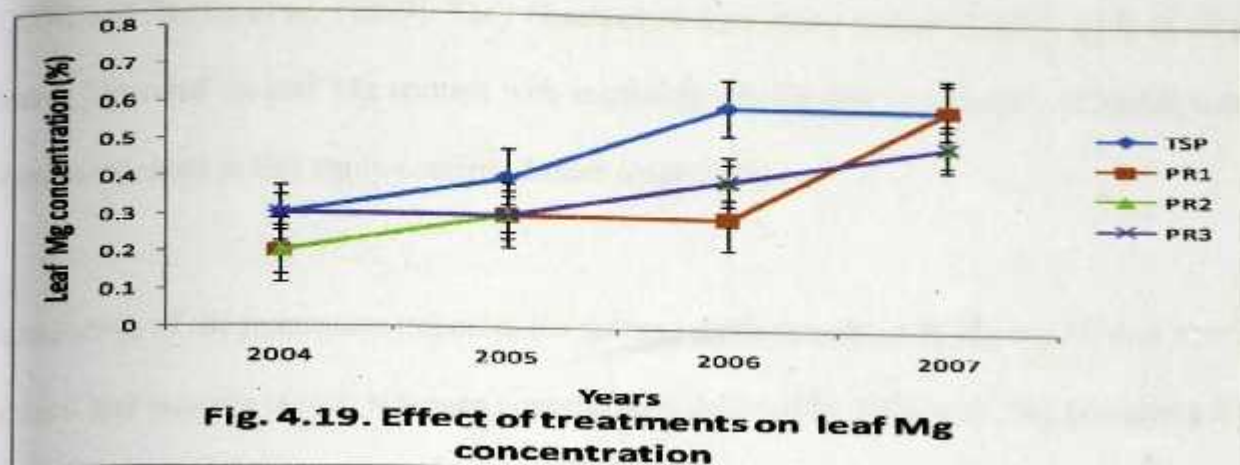
4.5 DYNAMICS OF OIL PALM NUTRIENT CONCENTRATION

4.5.1 RESULTS

The dynamics of oil palm leaf nutrient concentration during the period of experimentation using frond number 17 is presented in Fig. 4.16 to Fig. 4.20. Treatments did not significantly affect leaf N, P, Mg and Ca content. Leaf K concentration for the period 2006 and 2007 were significantly ($P < 0.05$) influenced by treatments. There was initial increase in leaf N concentration from 2004 to 2006 but the trend declined in 2007. This is typical of oil palm as N concentration in leaves decreases as the palm ages. For P, all the treatments from 2005 to 2007 recorded values above the critical level of 0.15 % (IRHO, 1960). From 2006 to 2007 leaf P concentration declined except treatment PR1 which increased by 13 % (Fig. 4.17). There was a gradual increase in leaf K from 2004 to 2007 except treatment TSP (control) which declined from 0.17 to 0.14 %. Gradual increase in leaf Ca concentration was also recorded in this study (Fig. 4.20). Leaf K and Ca contents for all treatments were below the percent deficiency threshold of 1.0 and 0.6 % respectively (IRHO, 1960). Generally, there was a gradual increase

for leaf Mg content during the study period except TSP treatment (control) which decreased by 14.5 % from 2006 to 2007 (Fig. 4.19).





4.5.2 DISCUSSION

The frond number 17 was used to determine the dynamics of oil palm nutrient concentration. Of all the nutrients analyzed (N, P, K, Mg, Ca), Ca and K were below the critical nutrient levels of 0.6 and 1.0 % respectively (IRHO, 1960). The low levels could be attributed to the low contents of Ca and K in the soil medium which fell far below the threshold deficiency levels. Noggle and Engelstad (1972) observed in their fertilizer experiment that, in cases of severe deficiency of nutrients in the soil, nutrient concentration in plants decreases. Levels of Ca in PR treated plots were comparatively higher than TSP treated plots. This was in agreement with results obtained by Sale and Mokwunye (1993) who reported that, PR plays a vital role in meeting the Ca needs of soil and crops.

Antagonistic effects in plant nutrient levels have been reported by authors like Bah and Zaharah (2004) and Havlin *et al.* (1999). They observed in their study that availability of K in oil palm leaves depended on leaf Mg content with increasing Mg leading to reduction in leaf K content. Results obtained in this study confirmed their observation.

Irrespective of the treatments imposed, the nutrient concentration of P, Mg and N were above the critical leaf nutrient levels. Nitrogen concentration declined by 2007 with PR1 producing further below the deficiency threshold level of 2.50 % (IRHO, 1960). This confirmed the findings by Nuerter (1999). In his study, he observed that the N nutrient levels in frond No.17 decreased as the palms aged. Phosphorus nutrient concentration was very promising for palms in PR treated plots (PR1, PR2 and PR3) with PR2 being the highest. This could be attributed to sustainable supply of P to palms by the PR. Bolan *et al.* (1990) made a similar observation where application of PR ensured continuous supply of P to palms for a long period.

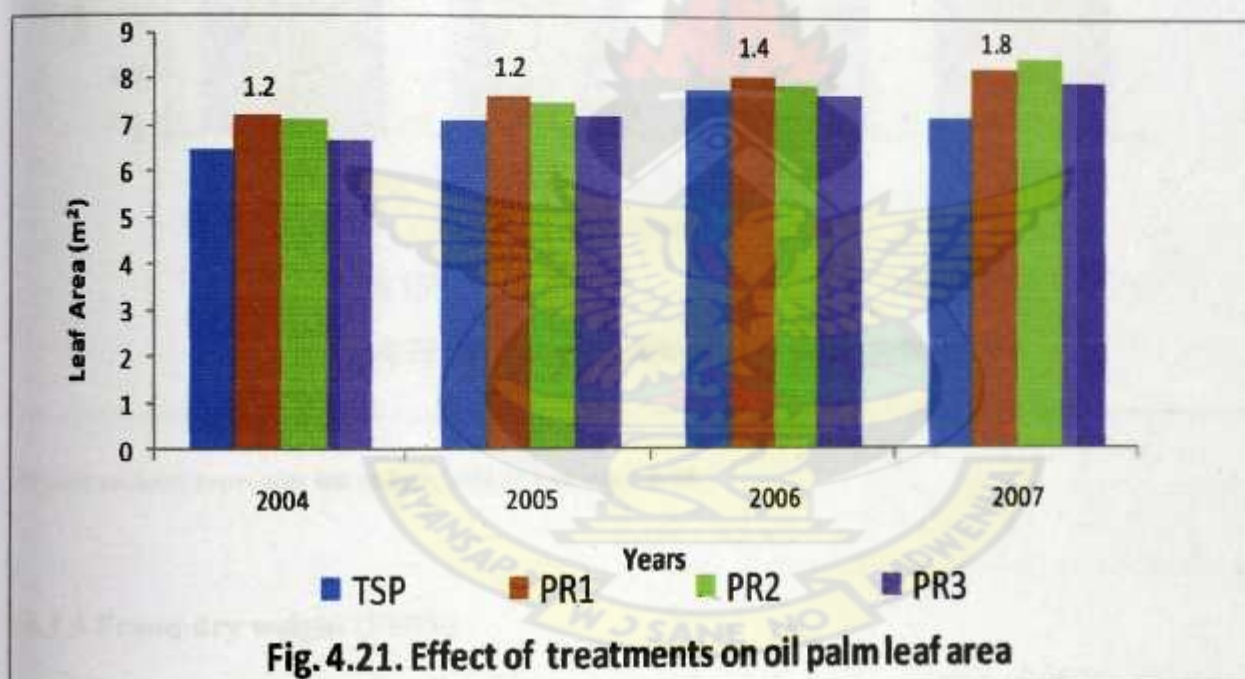
Fertilizer recommendation studies by Council for Scientific and Industrial Research-Oil Palm Research Institute (1986) indicated that mature oil palm may not need Mg since percent leaf Mg concentration is generally above the critical leaf nutrient levels of 0.24 % (IRHO, 1960). The results confirmed the above observation since leaf Mg concentrations were above 0.24 % throughout the period of experimentation except for PR1 and PR2 in 2004.

4.6 GROWTH AND YIELD OF OIL PALM

4.6.1 RESULTS

4.6.1.1 Leaf area (LA) development

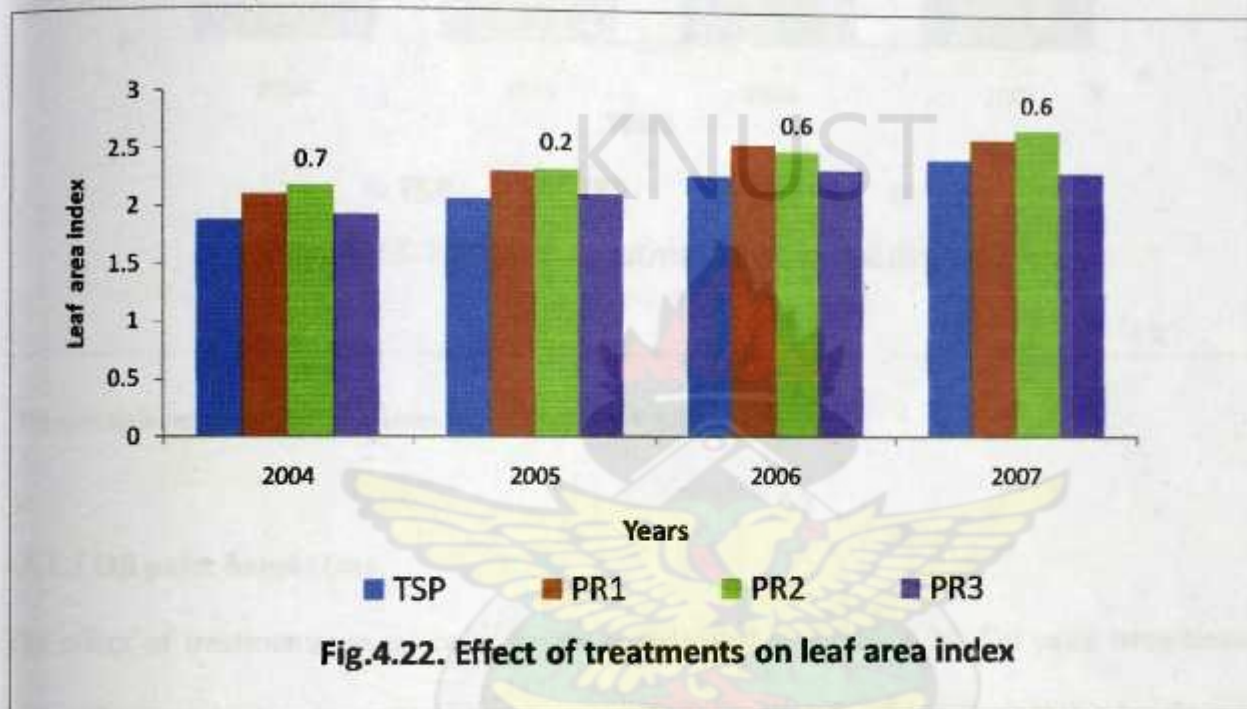
Figure 4.21 shows the effect of treatment on leaf area. Treatments did not significantly affect leaf area throughout the experimental period. Over the period, the highest and the lowest leaf area values of 8.52 and 6.45 m² were recorded by treatment PR2 and TSP respectively. Mean leaf area per palm in 2004 was 6.84 m². This increased to 9.0, 7.1 and 14.2 m² in 2005, 2006 and 2007 respectively.



Figures on bars represent lsd values. Where Lsd = $p < 0.05$

4.6.1.2 Leaf area index (LAI)

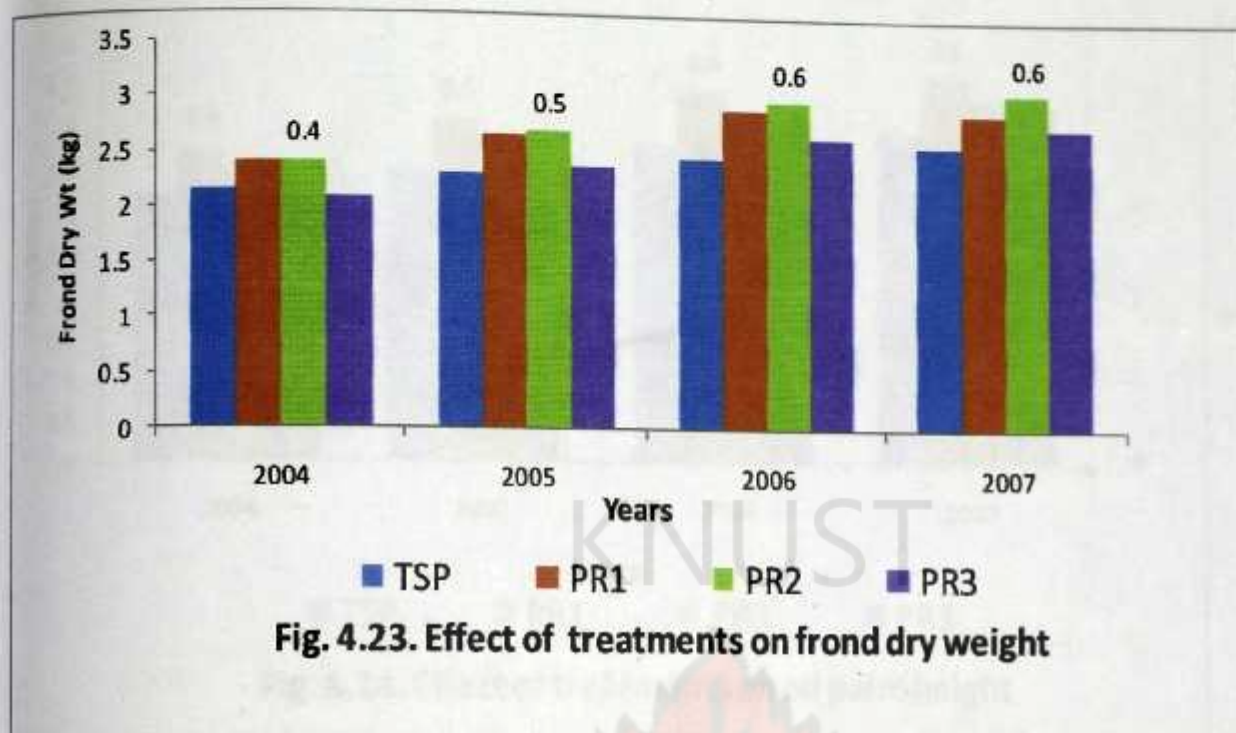
The effect of treatment on leaf area index is presented in Figure 4.22. During the period of the trial PR2 recorded the highest LAI of 2.67 with 1.88 recorded as the lowest for TSP. However, there were no significant differences ($P>0.05$) among treatments.



Figures on bars represent lsd values. Where $Lsd = p < 0.05$

4.6.1.3 Frond dry weight (FDW)

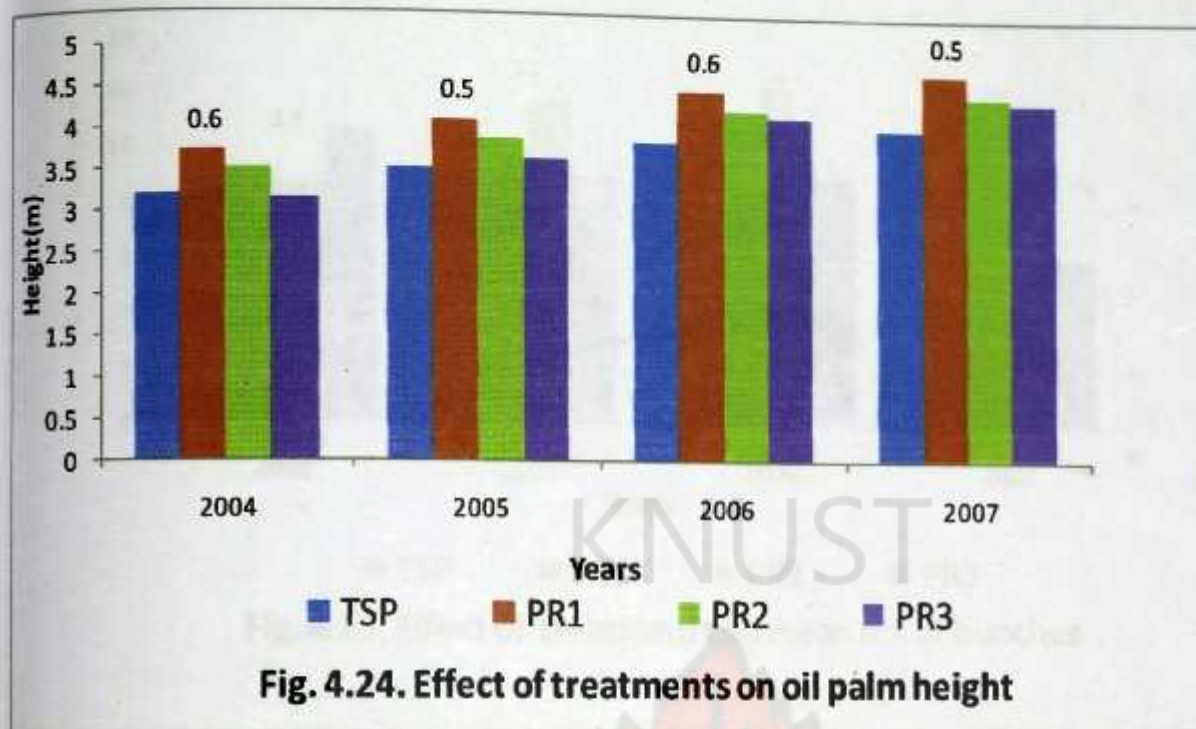
Figure 4.23 shows frond dry weight (FDW) as affected by treatments. The FDW of oil palm was not significantly affected by the treatments ($P>0.05$). Rate of increase in FDW was highest in PR2 treatment and lowest in TSP.



Figures on bars represent lsd values. Where $Lsd = p < 0.05$

4.6.1.4 Oil palm height (m)

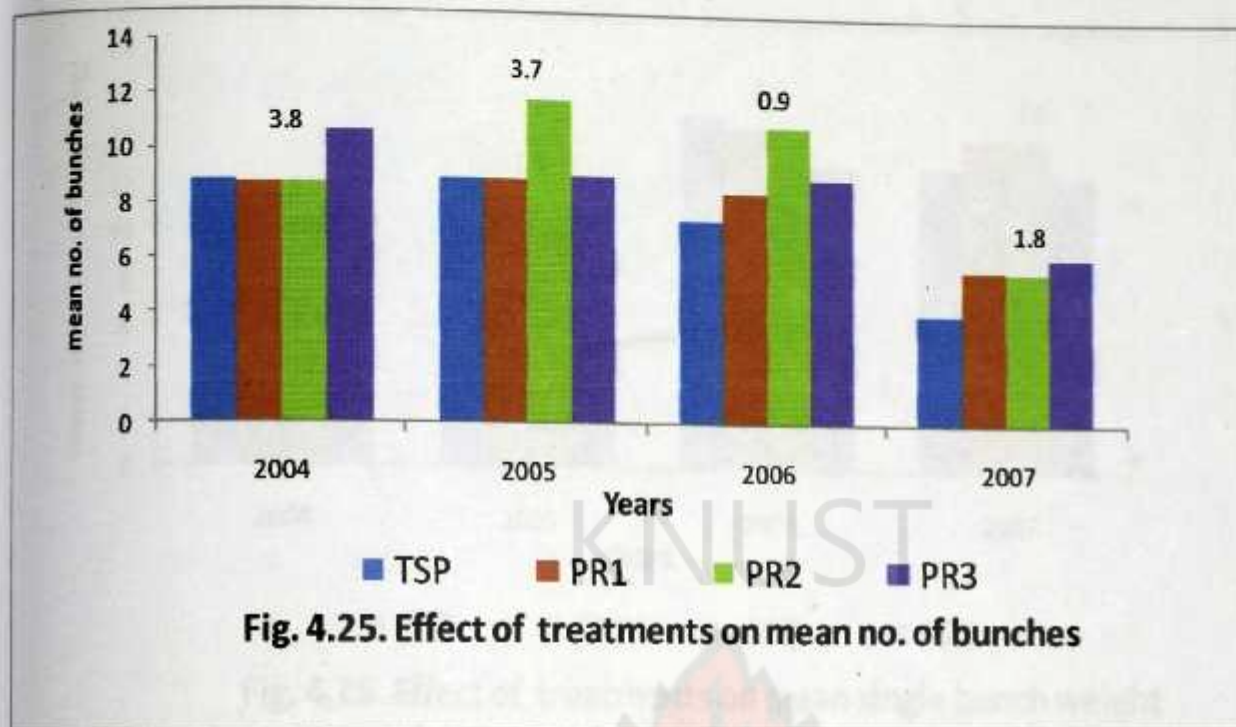
The effect of treatments on oil palm height is indicated in Figure 4.24. Oil palm trees treated with PR were higher than palms that received TSP treatments. The differences in height were however not significant ($P > 0.05$). The pattern of oil palm growth for the different treatments from 2004 to 2007 were the same, an indication that the growth in 2004 was mirrored in the subsequent years.



Figures on bars represent lsd values. Where $Lsd = p < 0.05$

4.6.1.5 Number of bunches per palm

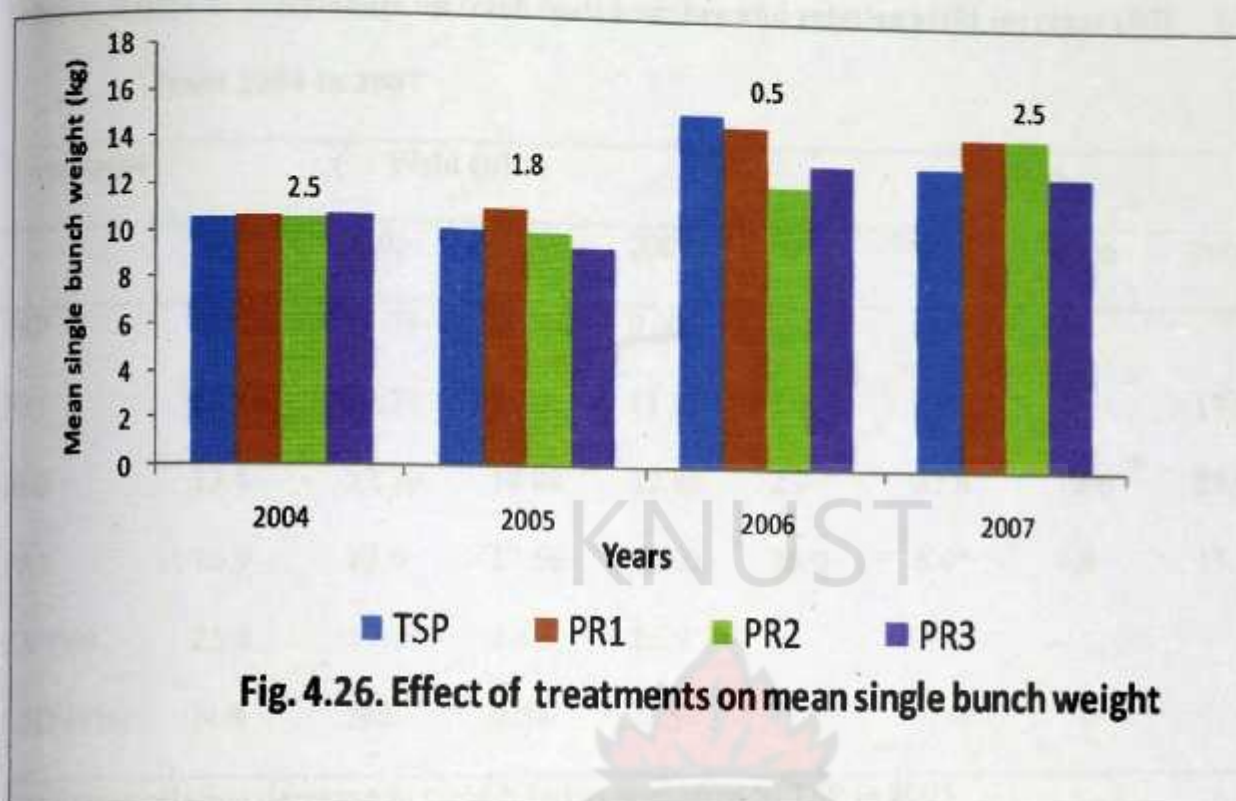
Figure 4.25 shows the mean number of bunches per palm as affected by treatments. The number of bunches per palm produced varied significantly ($P < 0.05$) among treatment means for 2004 and 2006 but differences were not significant in 2005 and 2007 (Figure 4.25). The average number of bunches produced per palm in 2004 was 11.0 for PR3. This was about 20, 22 and 19 % higher than the values for TSP, PR1 and PR2 treatments respectively. Thus, the number of bunches produced per palm greatly influenced the yield of fresh fruit bunches in this study. Generally, the mean number of bunches decreased as the palm ages and this is typical of the physiological growth and development of oil palm.



Figures on bars represent lsd values. Where $Lsd = p < 0.05$

4.6.1.6 Single bunch weight (kg)

Figure 4.26 shows the mean single bunch weight as affected by treatments. There were no significant differences ($P > 0.05$) among treatments except in 2006. The highest mean single bunch weight of 14.5kg was recorded in 2006 by treatment TSP with the lowest of 9.3kg being recorded in 2005 by treatment PR2.



Figures on bars represent lsd values. Where $Lsd = p < 0.05$

4.6.1.7 Yield (t/ha)

The yield of oil palm defined as the product of the number of bunches and weight of bunches per ha from 2004 to 2007 is shown in Table 5. Fresh fruit bunches per ha was not significantly different among treatments except in 2006. The highest fresh fruit bunches per ha of 18.88 t/ha was recorded in 2006 for PR2 whilst the lowest of 9.92 t/ha was recorded in 2007 for TSP (control). In calculating the relative yield increase (RI) of PR treated plots, TSP treated plots were used as standard treatment. The RI during the early stages of the trial (2004) for PR1, PR2 and PR3 were 6.0, 2.0 and 25.0 % respectively. By 2007 the values had increased to 17.5 and 28.9 % for PR1 and PR2 respectively with PR3 recording a decreased value of 13.1%. For the years 2004 and 2007, RI were in the order of $PR3 > PR1 > PR2$ and $PR2 > PR1 > PR3$ respectively.

Table 5. Effect of treatments on fresh fruit bunches and relative yield increase (RI) from 2004 to 2007

Treatment	Yield (t/ha)				R1%			
	2004	2005	2006	2007	2004	2005	2006	2007
TSP	13.5	13.53	16.76	9.93	-	-	-	-
PR1	16.0	14.70	18.61	11.67	6.0	8.6	1.1	17.5
PR2	13.8	17.30	18.88	12.80	2.0	27.8	12.6	28.9
PR3	16.9	12.6	17.56	11.23	25.0	6.0*	4.8	13.1
CV (%)	25.8	17.1	1.6	23.9				
LSD (5%)	N.S	N.S	0.58	N.S				

* indicates relative decrease in yield (t/ha) as compared to TSP in 2005

4.6.2 DISCUSSION

Influence of treatments on growth and yield of oil palm

The soil used for the study was deficient in P (Table 3) and therefore application of P fertilizer tended to reduce this limiting factor of growth. Similar results have been reported by Menon and Chien (1993). In their study, they observed an increase in yield of maize after a finely ground PR compacted with TSP had been applied to a phosphorus deficient acidic Ferralsols.

Variations in vegetative growth parameters (leaf area, leaf area index, frond dry weight and height) and yield components (number of bunches, single bunch weight and fresh fruit bunches) during the period of study were due to differences in water soluble P content of P fertilizer

sources. As shown in Table 4, TSP had the highest water soluble P (17.2 %) while PR was nearly insoluble (0.20 %).

It has been found that there is superior residual effect of PR compared to water soluble P (TSP) more especially in acidic soils (Sale and Mokwunye, 1993). Results from this study (Table 5) were consistent with their findings. Bolan *et al.* (1990) noted that incorporation of PR into the soil ensured a sustainable supply of P over a long period and also created a high rooting density for better nutrient exploration. This resulted in increased yield of 16.9 % (PR2) over TSP treated plots. Research done on PR in the United States provides an idea of the duration of the effect from residual P on a soil (Tisdale *et al.*, 1985). They provided data to show that irrespective of the rate of P, there was a residual effectiveness up to the seventh crop and response to initial and residual P increased with increasing rates. A similar observation was made in this trial where single application rate of 1428 kg PR + 222 kg AS + 296 kg of MOP once in 5 years (PR2) gave promising results both morphologically and reproductively. Similarly, in Brazil, a single application of PR per ha of land deficient of P gave 100 percent yield increase in oil palm over a period of 6 years (Hartley, 1988).

As found in this trial, PR was more efficient as compared to water soluble P fertilizers in terms of P uptake by oil palm. This observation agreed with that of Yeates (1993) who reported on better P uptake in plants treated with PR than water soluble phosphate fertilizers (TSP). Field trial results have indicated that ground PR was suitable for direct application on slightly acidic soils in the humid-tropical environment (Adediran and Sobulo, 1998). They found that PR increased crop yield and gave similar relative efficiency comparable to the conventional soluble P fertilizers.

Decrease in yield in TSP plots (control) could be attributed to very acidic conditions of soil (Figure 4.1a and Figure 4.1b). In 2007, PR treated plots (PR2) recorded a moderately acidic values of pH which made the crop better adapted for effective nutrient uptake resulting in good growth, development and yield of oil palm. Jacquemard (1998) observed that the oil palm can cope with acidic soils but is better adapted to near to neutral soil pH values.

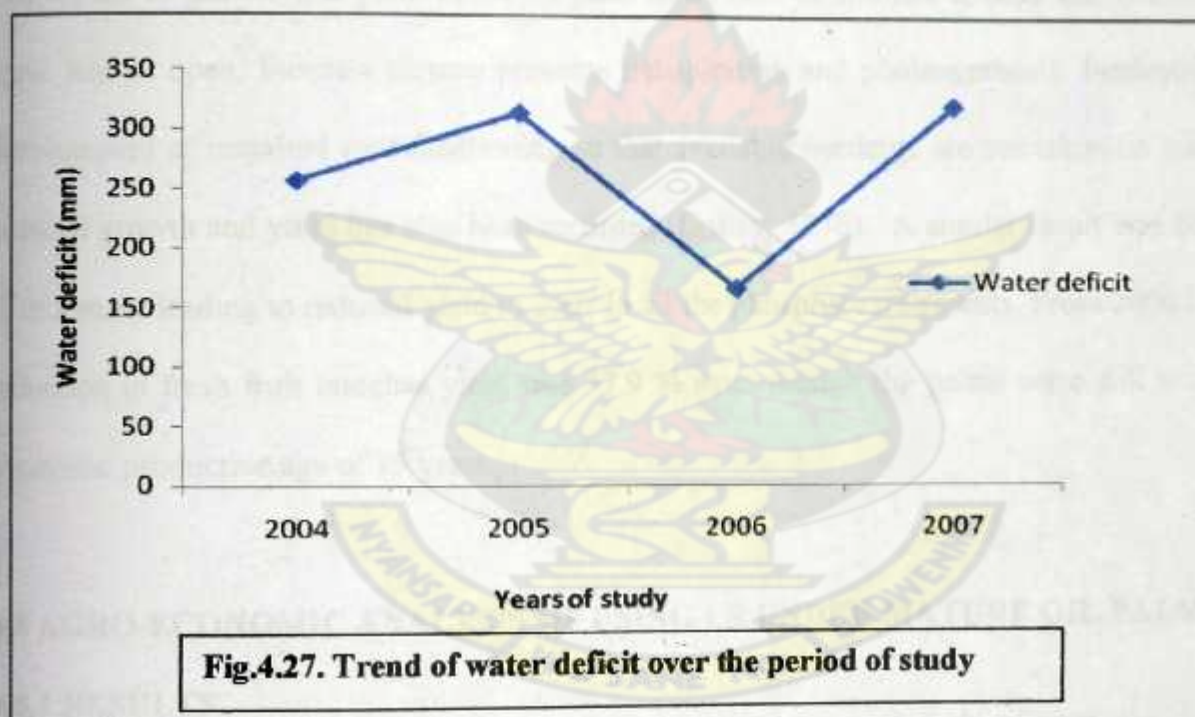
The overall response of oil palm to P fertilizers showed a higher fresh fruit bunch yield where PR was applied to the soil and was statistically better than the fresh fruit bunches yield produced by TSP (Table 5). This is in agreement with Sale and Mokyunye (1993) that, PR applied to the soil (such as P-deficient acidic Ferralsols encountered in the humid forest zone), dissolves readily to sustain plant growth.

Microbial biomass played a key role in maintaining soil fertility because its activity was the primary driving force for the biological cycles of almost all the major plant nutrients (Robert and Chenu 1991; He *et al.* 1997). Application of PR increased soil microbial biomass, probably due to adjustment of the soil pH from extremely acidic to strongly acidic conditions. This created a favourable environment for the growth and reproduction of soil microorganisms. Several investigators have reported that crop yields were highly correlated with microbial biomass through field experiments (Insam *et al.*, 1991).

4.7 INFLUENCE OF WATER DEFICIT ON OIL PALM PRODUCTIVITY

4.7.1 RESULTS

The annual water deficit which is the difference between the cumulative potential evapotranspiration and precipitation together with theoretical soil moisture reserves within a period at a specific place as captured during the period of experimentation is shown in Figure 4.27. The highest annual water deficit of 320.6 mm was recorded in 2007 while the lowest of 166.2 mm was also registered in 2006.



4.7.2 DISCUSSION

Van der vossen (1969), using values of mean annual water deficit, delineated areas climatically optimum for oil palm production in Ghana to have mean annual water deficit of 150 mm. Several authors have reported the detrimental effect of high water deficit on the growth and yield of oil

palm. In this study, increased annual water deficit of 313.7 mm in 2005 caused drastic reduction in yield in 2007 since typically in oil palm, treatment imposed physiologically shows their impact from 27 to 33 months later. Ochs and Daniel (1976) observed similar reduction in growth and yield of fresh fruit bunches produced in tenera oil palm under intermittent water stress which is sometimes irreversible. In this study decreased yield as a result of high water deficit could be attributed to excessive production of male inflorescence. This is similar to findings by Hartley (1988) who reported high water deficit (drought) leading to excessive production of male inflorescence with a consequent reduction in sex ratio (the proportion of female inflorescence to the total number of inflorescences produced). Ferwerda (1977) also reported that drought is detrimental to growth and yield in the oil palm as a result of stomata closure and failure of the spear leaf to open. Stomata closure prevents transpiration and photosynthesis. Inadequate root development or impaired root functioning so that available nutrients are not taken up leading to reduced growth and yield has also been recorded (Corley, 1976). A similar result was observed in this study leading to reduced yield in 2007 in all the phosphate treatments. From 2006 to 2007, reduction in fresh fruit bunches yield was 57.9 % even though the palms were still within the economic productive age of 25 years.

4.8 AGRO-ECONOMIC ANALYSIS OF USING PR UNDER MATURE OIL PALM

4.8.1 RESULTS

4.8.1.1 Establishment cost

Cost of establishing one hectare of oil palm with the cover crop pueraria amounted to about one hundred and thirty Ghana cedis, six persewas only (GH¢130.60) (Appendix 1). This was treated as fixed cost per treatment per hectare.

4.8.1.2 Upkeep, fertilization, harvesting and transportation cost

Table 6 presents upkeep, fertilization, harvesting and transportation cost for treatments. The cost of operations for the plots that received TSP (control) was GH¢ 197.70 in 2004. This increased to about GH¢ 227.8, GH¢ 253.2 and GH¢ 326.3 for the year 2005, 2006 and 2007 respectively.

Plots that received PR included PR1, PR2 and PR3 and the respective cost incurred were GH¢ 288.5, GH¢ 311.9 and GH¢ 164.3 for the year 2004. The cost values decreased and increased marginally for 2005 and 2006 respectively. In 2007 the cost incurred on PR treated plots received a further increase. The increases recorded in 2007 for treatment PR1, PR2 and PR3 values were GH¢ 284.1, GH¢ 241.9 and GH¢ 254.7 respectively.

Table 6. Upkeep, fertilization, harvesting and transportation cost per hectare of various treatments

Treatment	2004	2005	2006	2007	Total
	GH¢				
TSP (control)	197.7	227.8	253.2	326.3	1005.0
PR1	228.8	212.3	228.7	284.1	953.9
PR2	311.9	145.4	186.6	241.9	885.8
PR3	164.3	146.4	186.6	254.7	752.0

4.8.1.3 Yield and annual revenue from fresh fruit bunches of various treatments

Yield and annual revenue generated from the sales of fresh fruit bunches are presented in Tables 7 and 8 respectively. Prices of fresh fruit bunch fluctuated based on the world market price of crude palm. Total revenue generated for the treatments were in the increasing order of GH¢ 2,778.5, GH¢ 3,033.0, GH¢ 3,168.6 and GH¢ 3,197.8 for TSP, PR3, PR1 and PR2 respectively.

Table 7. Yield and fresh fruit bunches from various treatments

Treatment	2004	2005	2006	2007	Total
	t/ha				
TSP (control)	13.50	13.53	16.76	9.93	123.50
PR1	16.00	14.70	18.61	11.67	130.70
PR2	13.80	17.30	18.88	12.80	132.50
PR3	16.90	12.60	17.56	11.23	128.00

Table 8. Annual revenue from fresh fruit bunches of various treatments

Treatment	2004	2005	2006	2007	Total
	GH¢				
TSP (control)	621.0	608.9	754.2	794.4	2778.5
PR1	736.0	661.5	837.5	933.6	3168.6
PR2	634.8	760.5	778.5	1024	3197.8
PR3	777.4	567.0	790.2	898.4	3033.0

Source of sale prices: CSIR-Oil Palm Research Institute at Kusi (2004-2007)

4.8.1.4 Economic evaluation of using PR under oil palm during the period of the trial

The least gross income of GH¢ 2,778.5 was generated from plots that received TSP application (control) and this was enough to offset the production cost of GH¢ 1,135.6 (Table 9). Plots that received PR of 1428 kg/ha once in 5 years (PR2) gave the highest net income of GH¢ 3,197.8 and return per cash invested was 3.1. The economic returns or return per cash invested for the treatments during the period of study were in the order of PR3 > PR2 > PR1 > TSP (Table 9). Using TSP (control) as the basis for comparison, income equivalent ratio for TSP, PR1, PR2 and PR3 were 1.0, 1.1, 1.2 and 1.1 respectively.

Table 9. Economic evaluation of the oil palm as influenced by treatments

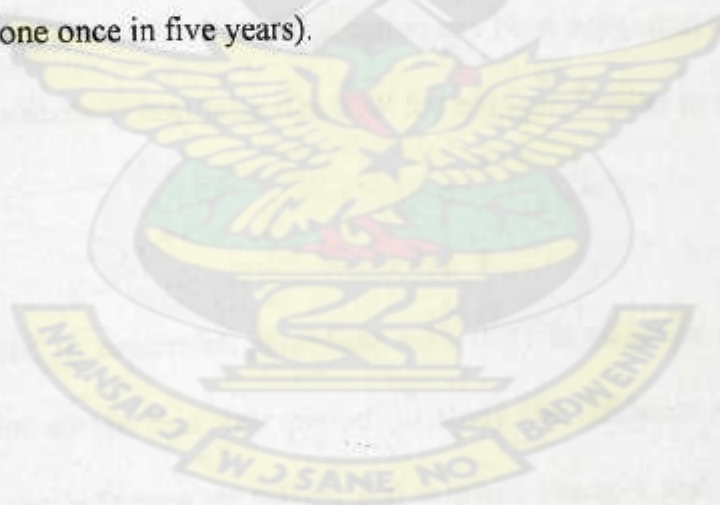
Treatments	TCP	GI	NI	RCI	IER
	GH¢				
TSP (control)	1135.6	2778.5	1642.9	2.4	1.0
PR1	1084.5	3168.6	2084.1	2.9	1.1
PR2	1016.4	3197.8	2181.4	3.1	1.2
PR3	882.6	3033.0	2150.4	3.4	1.1

(In the above economic evaluation, TCP = total cost of production, GI = gross income, NI = net income, RCI = return per cash invested and IER = income equivalent ratio).

4.8.2 DISCUSSION

According to Gerner and Baanante (1995), PR application by farmers is sustainable when it is profitable, socially acceptable and environmentally friendly. The cost benefit analysis of the trial during the period in increasing order for the various treatments were 2.4, 2.9, 3.1, and 3.4 for TSP, PR1, PR2, and PR3 respectively. There were higher net profit returns for all the PR treatments than TSP treatment (control). The PR2 recorded a net profit of about GH¢ 2,181.4 and

this was enough to re-invest about three times into the same project. The net income from the remaining PR treatments, PR1 and PR3 could offset about three times and three and half times of the total cost of production respectively. The least attractive treatment was reported by TSP treated plots (control). This was due to the high cost of the TSP component in the fertilizer applied. These results support the study conducted by Dahoui (1994), who concluded that the total cost per unit of P_2O_5 in PR is approximately half the cost per unit of P_2O_5 in TSP. The economic evaluation of PR under oil palm has also been carried out by Zin *et al.* (2005) in Malaysia. They observed that the return of cash invested in PR was better than TSP. During the period, PR2 could be considered as the most attractive for farmers in terms of profit as it exceedingly reduced the production cost. Despite the fact that the net income from PR3 was close to PR2, farmers will always opt for PR2 since additionally, it insulates them from market uncertainties and has an important advantage associated with time management (where the application of PR was done once in five years).



CHAPTER FIVE

5.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Potentially arable lands in Ghana are known to have highly weathered soils of low base saturation. These soils are in the humid rainforest agro-ecological zone of the country where oil palm is grown.

Next to N, P is the most limiting nutrient for oil palm production in these acid soils. The soil is deficient in total and extractable P. Adequate P fertilization is therefore essential for economic and sustained oil palm production in these soils. In Ghana and other developing countries, financial constraints have restricted the importation of chemical fertilizers and have created a situation in which fertilizers are not readily available or expensive. Exploitation of indigenous resources such as phosphate rock for direct application has been suggested to represent a cheap alternative to imported soluble P fertilizers like TSP for crop production in the acid soils of the humid tropics.

Field trial was conducted to determine phosphate rock (PR) fertilization effect on yield and development of oil palm within four year period, to study the influence of PR on microbial biomass, to determine the influence of PR on soil nutrient changes and to evaluate the PR economic benefit in oil palm cultivation in the semi-deciduous forest zone of Ghana.

The data on the physico-chemical properties of the soil indicated that due to excessive leaching and constant nutrient uptake by palms, the soil was highly acidic, low in available phosphorus and low in organic matter resulting in low effective CEC. The growth and development of oil

palm showed that the crop responded to P fertilization. Application of the P fertilizers gave significantly high growth and yield of the crop. Amongst the P fertilizers used, application of PR at the rate of 1428 kg per hectare once in every 5 years (PR2) was most effective. This was due to sustainable/constant supply of P to the crop. The least effective treatment was the TSP treatment owing to rapid leaching of P applied.

Microbial C, N and P were higher at the 4th year of study than during the 1st year of study. Generally, microbial values observed were higher in PR treated plots than TSP plots. This could be attributed to slightly acid pH values observed in PR treated plots.

The study has demonstrated that high annual water deficits adversely affect the development and yield of oil palm since photosynthetic ability of palms are seriously hampered. The trial has again revealed that Mg content in matured palms is not a problem since levels are always above the deficiency threshold. The use of PR positively influenced chemical properties of the soil especially increasing exchangeable cations and available P. The study has clearly shown that, agronomically and economically it is sound to use PR under matured oil palm. All the PR treatments gave better positive net revenue at the end of the study than TSP plots (control).

For future research work, it is recommended that the following aspects of PR use should be considered:

- i. Long term evaluation of Togo PR (above 4 years duration) under oil palm to determine their agronomic efficacy.
- ii. Evaluation of different phosphate rocks with varying reactivity under oil palm to determine their agronomic efficacy.

- iii. Evaluation of amended phosphate rocks at the oil palm nursery and under established plantation conditions.
- iv. Evaluation of phosphate rocks of different origin under different soil conditions under matured oil palm.
- v. The influence of phosphate rock on quality of crude palm oil.



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APPENDICES

Appendix 1: Establishment cost of 1 hectare oil palm

Item	Mandays	Quantity	Unit cost	Cost/ha
1. Land preparation:				
a) Under brushing	12		50 p	GH¢ 6
b) Felling	18		-do-	GH¢ 9
c) Chopping down crown	15		-do-	GH¢ 7.5
d) Cutting fire belt, burning, heaping and 2 nd burning	9		-do-	GH¢ 4.5
2. Lining and pegging including cutting of pegs	8		-do-	GH¢ 4.0
3. Cutting and fixing of wire Collars	4		-do-	GH¢ 2.0
3. Planting/Sowing:				
a) Oil palm DXP seedlings	3		-do-	GH¢ 1.5
b) Pueraria seeds	3		-do-	GH¢ 1.5
4. Cost of planting materials				
a) Oil palm DXP seedlings		148	35 p	GH¢ 51.8
b) Pueraria seeds		6.5 kg	32 p	GH ¢20.8
5. Transportation of Seedlings (5km radius)				GH ¢2.0
6. Rolls of wire collars		4	GH 9.7 p	GH ¢38.8
Total				GH ¢130.6

Appendix 2: Upkeep, fertilization, harvesting and transportation cost per hectare of oil palm yield.

	2004	2005	2006	2007	Total
1. Oil palm labour requirement	GH¢				
a. Ring weeding	25.5	27.5	30.0	32.0	115.0
b. Interrow weeding	30.0	30.0	35.0	40.0	135.0
c. Fertilizer application	25.5	27.5	30.0	32.0	115.0
d. Harvesting and pruning	35.0	40.0	50.0	50.0	180.0
e. Transportation of fresh fruit bunches	20.0	25.0	30.0	30.0	105.0
2. Fertilizer requirement					
a. Rock phosphate	84.4	84.4	84.4	84.4	337.6
b. Triple superphosphate	66.6	79.9	124.3	177.6	448.4
c. Muriate of potash	53.3	75.4	111.1	155.4	395.2
d. Ammonium Sulphate	53.3	75.4	124.3	155.4	408.4

Appendix 3: Mean monthly rainfall from 2004-2007

Month	Years			
	2004	2005	2006	2007
	mm			
January	32.4	0.2	60.2	0.0
February	43.6	40.6	73.6	10.0
March	122.4	134.7	149.8	61.6
April	85.6	110.0	111.6	165.3
May	269.8	181.4	369.6	249.4
June	67.8	219.2	74.6	202.2
July	63.8	21.2	69.2	83.8
August	87.2	31.0	50.0	182.0
September	356.2	59.2	287.9	311.0
October	276.4	182.8	229.6	381.1
November	154.6	125.8	68.8	154.7
December	73.8	46.4	59.0	20.2
Total	1633.6	1152.5	1605.9	1821.5