SOIL PHOSPHORUS FRACTIONS AS INFLUENCED BY PHOSPHORUS AND NITROGEN SOURCES ON TWO SITES IN WESTERN KENYA

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DEDICATION

This Thesis is dedicated to my wife Anita, my daughter, Penina Nyaboke, sons, Nelson Mandela, Herman Onuko, parents, brothers and sisters.

DECLARATION

This thesis is my original work and has not been presented for a degree in any other university. No part of this thesis may be reproduced without the prior permission of the author, Moi University and or International Centre for Research in Agroforestry (ICRAF).

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ABSTRACT

The effects of inorganic phosphorus fertilizers on soil P fractions in the highly weathered soils of the sub-humid tropics are poorly understood. A study to evaluate effects of triple superphosphate (TSP, 20% P) and Minjingu phosphate rock (MPR, 13% P, 3% citrate-soluble P), on soil phosphorus fractions and their relationship to maize yields was conducted on a clay loam Oxisol and a sandy clay loam Alfisol in western Kenya. The two sources of P, applied at a basal rate of 0, 50 and 250 kg ha^{-1} each were combined with 60 kg N ha^{-1} applied as either urea or tithonia [*Tithonia diversifolia* (Hemsley) A. Gray] green biomass. Sequential and non-sequential extractable inorganic (Pi) and organic (Po) fractions were determined at the end of each cropping season. Microbial biomass P (MBP) and C (MBC) were determined on samples taken two weeks after fertilizer application. All the fractions were correlated against maize yield from the next harvest.

Phosphorus applied at the rate of 250 kg P ha^{-1}, as either TSP or MPR had a significant increase on the labile and moderately labile inorganic Pi fractions. Enrichment of Pi fractions above the control indicates that use of inorganic P fertilizers (either TSP or MPR) can substantially increase P in both the liquid capital (approximated by Resin + $NaHCO_3$ extractable inorganic P) and reserve capital (approximated by NaOH + HCl extractable inorganic P) fractions.

Extractable inorganic P varied between the P sources and sites. For example the TSP-treated soil, $NaHCO_3$-Pi and NaOH-Pi were the major P sinks in both soils, while for MPR treated soils the Resin and HCl extractable inorganic P fractions were highest in the Alfisol. MPR treatments showed moderate increases between the 2 seasons in both the labile (RP-Pi and $NaHCO_3$-Pi) and moderately labile (NaOH-Pi) fractions at both sites. Extractable Pi fractions from tithonia treatments were generally slightly higher than those from urea treatments. The organic P (Po) fractions were not influenced by the P rate, P source or N source (tithonia vs. urea).

Coefficients of determination (r^2) of P pools against maize yield were generally higher for TSP as compared with MPR on both sites. Non-sequential RP-Pi, $NaHCO_3$-Pi and $NaHCO_3$ + EDTA-Pi had stronger correlations with maize yield than Pi fractions from the sequential extractions in TSP-treated soils. Resin-Pi (both sequential and non-sequential) had the strongest correlations with maize yield in MPR-treated soils. The organic P fractions and microbial biomass fractions (P and C) were not significantly correlated with maize yields. The relative agronomic effectiveness (RAE), determined as increase of maize yield due to MPR divided by increase due to TSP, expressed as a percentage, varied with both site and season. The RAE of MPR (averaged over N sources) increased from 72% in season 1 to 92% in season 2 on the clay loam and decreased from 114% to 93% on the sandy clay loam. The RAE for MPR with tithonia as N source, averaged over both seasons, was 77% on the clay loam and 94% on the sandy clay loam, while with urea, RAE averaged 87% on the clay loam and 113% on the sandy clay loam.

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ACRONYMS AND ABBREVIATIONS

FAO	Food and Agriculture Organization of the United Nations
ICRAF	International Centre for Research in Agroforestry
KARI	Kenya Agricultural Research Institute
KEFRI	Kenya Forestry Research Institute
MCP	Mono-calcium phosphate
MPR	Minjingu phosphate rock
NAC	Neutral ammonium citrate
OSP	Ordinary super phosphate
P	Phosphorus
Pi	Inorganic phosphorus
Po	Organic phosphorus
RCBD	Randomized complete block design
RP	Resin extractable phosphorus
SED	Standard error of differences in means
TSBF	Tropical Soil Biology and Fertility
TSP	Triple superphosphate
UNESCO	United nations Educational, Scientific and Cultural Organization
USDA	United States Department of Agriculture

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CHAPTER ONE

1.0 INTRODUCTION

Phosphorus (P) is an essential element for plant growth and development. It is, however, generally deficient in highly weathered soils with acidic properties such as Ultisols and the Oxisols (Sollins *et al.*, 1988). This is particularly so in the humid and sub-humid tropics of sub-Saharan Africa where these soils are dominant (Deckers, 1993). In the Eastern Africa region, P deficiency is of common occurrence in the highly populated highlands (Bekele and Hofner, 1993). Estimates of P limitations in western Kenya range from 80-90% of the farms (Shepherd *et al.*, 1995)

The low levels of plant available P in soils of Sub-Saharan Africa and especially those in western Kenya are attributed to low native P, high P sorption capacities, nutrient depletion through removal by crop harvests with no corrective fertilizer inputs (Palm, 1995) and erosion of top soil by run-off water (Smaling *et al.*, 1993; Swift *et al.*, 1994). The low plant available P in these soils has contributed to declining food production (Shepherd *et al.*, 1995).

Inorganic P fertilizers applied singly or in combination with high quality organic materials have the potential to improve the P status of the soil through increasing the P concentration in soil solution (Murwira *et al.*, 1995) or through the complexation of P fixing sites by organic compounds (Sanchez *et al.*, 1997). Increase in P concentration in the soil solution generally leads to increase in crop yield (Jama *et al.*, 1997).

Soil P pools has been classified as either liquid or capital depending on their relative availability to crops (Baanante, 1997). Liquid capital P represents the relatively soluble P pools comprised of anion exchange resin extractable P (RP-Pi) and sodium bicarbonate inorganic P ($NaHCO_3$-Pi). These are relatively available for plant uptake and they constitute the bulk of the labile P pools. Reserve capital P is composed of the less soluble P pools, sodium hydroxide extractable inorganic and organic P (NaOH-Pi and NaOH-Po) and hydrochloric acid extractable P (HCl-Pi) that gradually become plant available over several cropping seasons (Buresh *et al.*, 1997). The two constituents of P capital are in equilibrium with each other and adjust to addition or removal of P from the system (Baanante, 1997). Application of inorganic P fertilizers can increase $NaHCO_3$ and NaOH extractable P when the rate of P addition exceeds P uptake by plants (Schmidt *et al.*, 1996) thus contributing to both liquid and reserve capital P pools.

Phosphorus from water-soluble sources such as triple superphosphate (TSP) is rapidly released to labile soil P or the liquid capital P. Application of phosphate rocks (PRs) such as Minjingu phosphate rock (MPR) classified as medium to highly reactive (Hammond and Leon, 1983) can increase NaOH-Pi and HCl-Pi or reserve capital P fraction in acid soils (Buresh et al., 1997). Liquid capital P from soluble phosphate rocks has also been noted to increase during the year of application (Hellums *et al.*, 1992).

Fast decomposing and nutrient-rich organic materials such as [*Tithonia diversifolia* (Hemsley) A. Gray] biomass have been suggested as alternative P sources for increasing P availability in soils with high P-fixing capacities (Szott and Kass, 1993; Jama *et al.*, 1997). They can be a source of organic phosphorus (Po) and inorganic phosphorous (Pi) with the former being subject to mineralization which releases inorganic P or forms organic P fractions (Iyamuremye and Dick, 1996). Tithonia is increasingly becoming a source of N as a substitute for urea in western Kenya. It is abundantly planted on farm boundaries and occurs naturally on roadsites.

Work done to determine the measurable soil P pools following fertilization with TSP, MPR and tithonia on an Alfisol that was both P and K limited in western Kenya showed that the organic and inorganic P pools were affected by P treatments alone (Mutuo *et al.*, 1999). In the same study, TSP was found to result in higher RP-Pi, $NaHCO_3$-Pi, and NaOH-Pi than MPR. Only RP-Pi and NaOH-Pi correlated well to maize yield. In another study, in the same area, Nziguheba *et al.* (1998) observed that tithonia biomass applied alone or in combination with inorganic P sources increased labile soil P while organic P sources applied alone decreased slightly the P sorption capacity of the soil in western Kenya. These studies were, however conducted at only one site which limits the ability to extrapolate the results to other areas.

Although several studies on P have been conducted over the years, a good understanding of P dynamics remains elusive in both natural and managed production systems (Beck, 1991). These shortcomings in studying P dynamics have, in part, been methodological in nature. The methods most frequently used are those that test for single and more labile P pools and ignore less available organic and inorganic P pools (Kamprath and Waston, 1980). However, the various P pools in soil can be distinguished through a sequential extraction using anion exchange resin, 0.5M sodium bicarbonate, 0.1M sodium hydroxide, and 1.0M hydrochloric acid (Hedley *et al.*, 1982; Tiessen and Moir, 1993).

In view of the above, a study to evaluate the various P fractions as influenced by two P sources (triple superphosphate and Minjingu phosphate rock) in combination with tithonia or urea as sources of N on two sites with contrasting soil properties near Maseno in western Kenya was carried out.

1.1 Broad objective

To compare the influence of P sources on soil P fractions as determined by various P extraction methods and determine their relationship with maize yield.

1.1.1 Specific objectives

i. To determine the effect of TSP and MPR on soil P pools.

ii. To evaluate the influence of tithonia vs urea as sources of N on soil P pools.

iii. To determine the relationship between the various P fractions and crop yield on two soils.

1.2 Hypotheses

i. Fractions of P extracted in a sequential P fraction scheme are a good approximation of rapidly and moderately available P in soils receiving organic inputs and P sources of different solubility in soils.

ii. Fast decomposing and phosphorus-rich organic materials enhance P availability in soils.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Forms of soil phosphorus

Soil phosphorus can be classified generally as organic or inorganic depending on the nature of compounds in which it occurs. The organic fraction is found in humus and other organic materials that may or may not be associated with humus. The inorganic fraction of soil P occurs in numerous combinations with Fe, Al, Ca, F and other elements (Tisdale *et al.*, 1985). Solubility of these compounds in water varies from sparingly soluble to very insoluble. Phosphorus reacts with clay minerals to form generally-insoluble clay-phosphate complexes.

2.1.1 Inorganic Phosphorus

The ultimate source of soluble inorganic P (Pi) in soil is the dissolution of primary P minerals, mainly apatite [$Ca_{10}X_2(PO_4)_6$, where X=OH^- or F^-]. Soil solution P is usually in the form of primary ($H_2PO_4^-$) and secondary (HPO_4^{-2}) orthophosphates. Once in soil solution, Pi can be: (i) taken up by plants (ii) taken up by soil biota and converted to organic P (Po), (iii) sorbed onto soil colloids or (iv) form sparingly soluble inorganic P compounds.

Two phenomena tend to control the concentration of Pi in soil solution and movement of Pi in soil. These are (i) the solubility of P containing minerals and (ii) the fixation or adsorption of phosphate ions on the surface of soil particles. The sorption of Pi occurs mainly on hydrous oxides or under certain circumstance structural Al at the edges of 1:1 silicate clays (e.g. kaolinite).

The inorganic P fractions in the soils may be determined and distinguished through sequential P fractionation schemes (Chang and Jackson, 1957; Hedley *et al*, 1982; Tiessen and Moir, 1993) as anion exchange resin, 0.5 M sodium bicarbonate, 0.1 M sodium hydroxide and 1.0 M hydrochloric acid. The resin extractable Pi is directly exchangeable with soil solution. It is a pool from which plants readily take up P. Bicarbonate extractable Pi is loosely sorbed on the surface of soil particles (Mattingly, 1975). Both pools represent labile Pi that is readily plant available. Hydroxide extractable Pi is strongly sorbed onto Fe and Al oxides and clay surfaces (Williams *et al.*, 1980). NaOH Pi has lower plant availability (Marks, 1977) and is thought to be associated with amorphous and some crystalline Al and Fe phosphates. The hydroxide Pi pool increases in importance with soil weathering due to increased Fe and Al oxides and sorption of P in weathered soil materials. This pool represents a slowly labile Pi pool within the time frame of 2 - 20 years. Dilute HCl extractable Pi represents P from calcium phosphates (Tiessen and Moir, 1993). They comprise a large portion of total Pi in young soils but they are relatively unimportant in highly weathered soils (Tiessen and Moir, 1993; Cross and Schlesinger, 1995). However, a more precise characterisation of these Pi forms is usually not possible since mixed compounds containing Ca, Al, Fe and other ions predominate in soils (Sawhney, 1973).

2.1.2 Organic Phosphorus

The organic P fraction is found in humus and other organic materials. The levels of organic P in the soil vary enormously ranging from virtually 0 to over 40% of the total P (Tisdale *et al.*, 1985).

The nature and reactions of organic soil P are not as well understood as those of inorganic soil P. Soil biota are the driving force for the conversion of Pi to organic compounds and the subsequent mineralization of Po to Pi (Stewart and Tiessen, 1987). Much of the P associated with soil biota is contained in bacteria and fungi. The soil solution Po concentration can exceed Pi concentration in soil solution due to lower sorption of Po. Organic P is, however, much higher in organic soils than in highly weathered mineral soils. In addition, the organic P content of mineral soils is usually higher in the soil surface horizon than it is in the subsoil, because of the accumulation of organic matter in the upper parts of the soil profile (Tisdale *et al.*, 1985).

Sodium bicarbonate and sodium hydroxide are two extractants commonly used in attempts to isolate labile Po. Bicarbonate Po is easily mineralizable to plant available P (Bowman and Cole, 1978). Hydroxide Po contains P associated with humic compounds (Cross and Schlesinger, 1995). Hydroxide Po is more stable than bicarbonate Po, but it can be an important source of P for soil micro-organisms especially when labile Pi is low (Chauhan *et al.*, 1981). The NaOH-Po is thought to be involved in long term P transformations in temperate soils (Batsula and Krivonosova, 1973) but undergoing seasonal transformations in tropical soils (Ball-Coelho *et al.*, 1993).

In a comparison of fallow and cropping systems on an Oxisol in Brazil, bicarbonate Pi remained relatively constant regardless of cropping history whereas hydroxide Po reflected changes in SOM due to cultivation (Tiessen *et al.*, 1992). Beck and Sanchez (1994) working on a Peruvian Ultisol concluded that hydroxide Po was the dominant source of plant available P in an unfertilized 18-year-long cropping system. Hydroxide Po appears to represent a slowly labile P pool that is an important source of mineralizable Po within the time frame of 2 to 20 years in tropical soils (Beck and Sanchez, 1994). It does contribute significantly to crop P uptake under tropical conditions (Adepetu and Corey, 1976) and plays a major role in the short term P fertility of highly weathered soils (Tiessen *et al.*, 1992).

2.2 Phosphatic fertilizers

2.2.1 Superphosphates

There are two main types of superphosphate fertilizers, the ordinary superphosphates or single superphosphates (OSP) and triple or concentrated supersphosphate (TSP) Superphosphates are neutral fertilizers in that they have no appreciable effect on soil pH as do phosphoric acid and ammonium-containing fertilizers.

Ordinary superphosphate is manufactured by reacting sulphuric acid with rock phosphate. This product is essentially a mixture of monocalcium phosphate and gypsum, contains 7 - 9% P (16 - 22% P_2O_5), of which about 90% is water soluble and is essentially all classified as plant available. In addition, it contains about 8-10% sulphur as calcium sulphate. In areas in which the soils are deficient in S, the gypsum content has been an important contributor to satisfactory crop responses (Tisdale, 1985). Ordinary superphosphate is used largely in the production of mixed fertilizers in which other dry powdered, or finely granular materials are blended to effect a product that contains nitrogen, phosphorus and potassium. It is also used for direct application (Tisdale, 1985).

Triple superphosphate is manufactured by treating phosphate rock with sulphuric acid to give orthophosphoric acid, which is then reacted with phosphate rock to give TSP. It contains 19-23% P (44-52% P_2O_5), 95 - 98% of which is water-soluble and nearly all of which is classified as available (Tisdale *et al.*, 1985). Triple superphosphate dissolves rapidly in soil and is, therefore, immediately plant available. It is, however, progressively subject to fixation in soil over time, and supplies only small amounts of residual P for subsequent crops. Its high P content makes it particularly attractive when transportation, storage and handling charges make up a large fraction of the total fertilizer cost.

2.2.2 Phosphate rocks

Phosphate rock (PR) is obtained by mining deposits of phosphate rocks. Phosphate rocks are found to differ widely in their mineral composition with the main one being apatite (Khasawneh and Doll, 1978). The most important mineral fetilizers are fluoro-apatite or hydroxy-apatite or a mixture of the two with a general formula of $Ca_{10} (PO_4)_6X_2$, X= F or OH (Cook *et al.*, 1990). Deposits of PRs exist in East Africa but they vary in their effectiveness as P sources (Van Kauwenberg, 1991). The most suitable East African PR deposit for direct application is the Minjingu Phosphate Rock (Van Kauwenberg, 1991). Minjingu PR is a biogenic-sedimentary deposit in northeastern Tanzania, southeast of Lake Manyara. Minjingu PR was formed from P-rich solutions derived from guano and alkaline water precipitates. It has a P content of approximately 13% and neutral ammonium citrate (NAC) solubility of 3.0 % P_2O_5 (Van Kauwenberg, 1991). This makes it suitable for direct application in suitable soils (Khasawneh and Doll, 1978).

Phosphate rock is applied as a finely ground powder in order to increase the surface areas for fast dissolution and reaction It is usually sparingly soluble in water compared to water-soluble P fertilizers. Directly-applied PR is most effective in acid soils (Khasawneh and Doll, 1978).

The rate and extent of PR dissolution in the soil is enhanced by a pH lower than 5.5 (Anderson *et al.*, 1985; Kanabo and Gilkes, 1987), high amounts of reserve acidity (Bolan and Gilkes, 1990; Bolan and Hedley, 1990; Gahoonia *et al.*, 1992; Haynes, 1992) and low exchangeable calcium (Robinson *et al.*, 1992). Factors inherent to the PR also affect its dissolution, e.g., mineral composition (Anderson *et* *al.*, 1985) and particle size (Syer and Mackay, 1986). Other factors that affect PR dissolution include the period of PR reaction with the soil (Chien *et al.*, 1990), the rate at which it is applied (Rajan *et al.*, 1991) and the soil water content (Weil *et al.*, 1994).

Much of the initial dissolution of PR is rapid, occurring within a few days under laboratory conditions, followed by a much slower rate of dissolution (Smyth and Sanchez, 1982; Kanabo and Gilkes, 1988).

Working with acid Brazilian soils, Smyth and Sanchez (1982) found the highest reactivity of PR occurring on soils that had the lowest amount of Olsen extractable P, and the highest amount of clay and free iron oxide (Fe_2O_3) content. These characteristics indicate a high P sorption capacity. Other soil factors that are reported to enhance PR solubility are related to soil high organic matter (Chien *et al.*, 1990). Composting of agricultural wastes with PRs is known to increase solubility of PRs (Ikerra *et al.*, 1994). Availability of P from phosphate rock to plants has been enhanced when mixed with organic matter such as compost (Iyamuremye and Dick, 1996). Phosphate rock is likely to be solubilized by biological activity and production of organic acids during composting. The principle underlying the above processes is the production of organic acids which create a localized high acidity in the immediate vicinity of PRs and also complex Ca in the case of some organic acids. Organic acids produced during chemical transformations of organic debris dissolve the phosphates (Ca-, Fe-, Al-phosphates) not only by supplying protons but also by complexing the cations. This could also be the result of the chelation of the metals associated with P in the PRs. The increase in P availability from phospho-compost results from both conversion of PR-P to water soluble P and other less soluble Pi fractions.

From some work in Tanzania, by Patel (1975), crop responses to MPR, although erratic, are highest on relatively light textured soils derived from acidic parent materials. These soils are generally low in soil pH, low available Ca, and low in available P, all soil factors that are known to promote the dissolution of P from PRs.

2.3 Phosphorus extraction methods

2.3.1 Background

The use of extraction procedures to estimate the size of a nutrient pool that affects plant growth is an old concept (Kamprath and Watson, 1980) dating back over 200 years (Schnitzer, 1991). Among the major mineral nutrients, P is the one for which many different extraction procedures have been developed that relates nutrient pool to plant growth. An exhaustive review of extraction methods by a working group in Spain (Anon, 1982) listed 50 different methods and more than 50 different publications comparing different extractions. The most widely used P tests (active extractants) are Bray 1 (Bray and Kurtz, 1945), Mehlich-1 (Nelson *et al.*, 1953), and Olsen (Olsen *et al.*, 1954). However, all these tests have certain limitations and their ability to predict available P in soils with widely differing properties is sometimes limited (Fixen and Grove, 1990). Furthermore, these tests were developed to aid fertilizer recommendations in soils fertilized with water-soluble fertilizers. They may therefore not work as well in soils fertilized with sparingly soluble phosphate rocks (PRs) and partially acidulated phosphate rocks (PAPRs) (Chien, 1978; Hammond *et al.*, 1986; Mackay *et al.*, 1984).

The ideal soil tests are those that closely reflect the nutrient uptake of a large selection of crops and that are relatively insensitive to soil properties. Conventional soil tests rely on the use of extracting solutions that are capable of extracting specific forms of P by increasing solubilization of phosphates. The differences noted in performance of various soil test procedures in soils treated with soluble P or PRs arises because the two types of P sources leave different types and amounts of residues in the soil (Menon and Chien, 1995). Soluble P fertilizers are mostly sorbed by soil constituents. The PR not dissolved remains as apatite in the soil. When partially acidulated phosphate rocks (PAPR) or (PR + TSP) is used, the monocalcium phosphate (MCP) part of the fertilizer residue will dissolve rapidly and be sorbed by the soil constituents whereas the PR part which has not been dissolved will remain in the soil as apatite. Apatites are dissolved by acids but not by bases such as NaOH or $NaHCO_3$. Therefore, the Olsen test gives a measure of only the reaction products of PR and not the residual PR in soils fertilized with PR (Saggar *et al.*, 1992). In contrast, because the strongly acid reagents like Bray II and Truog extractants dissolve more residual P from apatite than may be bioavailable, they often overestimate P availability (Bationo *et al.*, 1991).

The objective of the numerous chemical extraction and ion exchange resin procedures is to evaluate labile P, the portion of soil P that is in equilibrium with soil solution (Sharpley *et al.*, 1994) and relate the same to plant growth (Kamprath and Watson, 1980). By means of extensive field trials, soil P test levels resulting from various P application rates are correlated to the relative yields of the crop grown and a critical soil P test level is established for specific crops.

Differing soil chemical properties and preferences across the world lead to different soil test procedures. Kamprath and Watson (1980) reviewed the most commonly used conventional soil P tests listing their strengths and weaknesses for use on different soils. A common feature among most of these procedures is that only inorganic P (Pi) is measured. This may partly explain why correlation of crop yield with soil P test level and the establishment of critical levels have not been successful on some highly weathered soils of the tropics (Gijsman *et al.*, 1996). Organic P pools (Po) have also been found to influence crop yields, especially in unfertilized land-use systems of these soils (Tiessen *et al.*, 1992; Cross and Schlesinger, 1995; Beck and Sanchez, 1994).

Although single extraction procedures have been widely used, the interpretation of P dynamics by extracting a single inorganic P pool, measured over time, is limited to comparison of established critical levels for certain annual crops to the levels measured and how these change over time. In the tropics where organic P may contribute substantial portions of available P to plant growth (Tiessen *et al.*, 1984) or where plant extraction of soil P does not correlate with the measured labile inorganic P levels (Tiessen *et al.*, 1992; Ball-Coelho *et al.*, 1993), single extraction values have little meaning.

2.3.2 Non-sequential P extraction methods

2.3.2.1 Anion resin exchange extractable phosphorus

Anion exchange resin was the first non-chemical extraction procedure proposed as a P soil test (Sibbesen, 1978). Resin also dissolves solid phase PR (Khasawneh and Doll, 1978; (Mutuo *et al.*, 1999). Anion resins remove P from soils without chemical alterations or pH changes. Amounts of P desorbed by resin has been used as a measure of plant available P in soils (Dalal and Hallsworth, 1976). Resins have also been used to assess the availability of residual phosphates (Bowman and Olsen, 1979) and to measure the rate of P release from soils (Gunary and Sutton, 1967) and the buffer capacity of soils (Brewster *et al.*, 1975). Phosphorus desorption by an ion exchange resin is a useful method to approximate P uptake by roots and measure availability of residual phosphates.

Resin P is found to be correlated well with plant P uptake in most soils (Bowman *et al.*, 1978; Olsen and Sommers, 1982) but analytical difficulties with the resin method prevent its use on a routine basis in many soil testing laboratories (Lin *et al.*, 1991).

2.3.2.2 Sodium bicarbonate extractable phosphorus

Phosphorus is extracted from the soil with 0.5M $NaHCO_3$ at pH 8.5 (Olsen *et al.*, 1954). In calcareous, alkaline or neutral soils containing Ca-phosphates, this extractant decreases the concentration of Ca in solution by causing precipitation of Ca as $CaCO_3$; as a result, the concentration of P in solution increases. In acid soils containing Fe and Al phosphates such as variscite and strengite, P concentration in soil solution increases as the pH rises (Lindsay and Moreno, 1960).

Secondary precipitation reactions in the acid and calcareous soils are reduced to aluminium because the concentration of Al, Ca and Fe remains at a low level in this extract. Moser *et al.* (1959) found a high correlation between $NaHCO_3$ extractable P and uptake of P by plants. Some sources of variation in the analytical results in the $NaHCO_3$ extraction method are associated with temperature of the extracting solution and the shaking method and speed.

2.3.2.3 Microbial biomass carbon and phosphorus

Soil microorganisms serve as sources and sinks of nutrients and their activities and turnover resulting from decomposition of organic materials are considered to be primary controlling factors in nutrient cycling and availability (Smith *et al.*, 1993). Addition of organic residues do increase microbial pool sizes and activity, C and N mineralization rates and enzyme activities (Smith *et al.*, 1993), all factors that affect nutrient cycling. Since C is often the element most limiting to microbial growth and activity in the soils the amount or C quality of organic additions will influence rates of nutrient cycling (Reinersten *et al.*, 1984).

Organic additions to the soil can also cause a shift in the distribution of nutrients in the organic and inorganic soil fractions caused by microbial activity. This redistribution might affect nutrient availability patterns and nutrient use efficiency, the net effect depending on the quality of organic addition. As an example Chauhan *et al.* (1981) and Hedley *et al.* (1982) measured changes in soil P fractions following addition of cellulose and N, plus or minus P. They concluded that for long term build up of soil P, it is necessary to add a C and a P source. Carbon provides substrate for microbial growth whose turnover results in the long-term accumulation of organic P especially in the more available P fractions.

The soil microbial biomass is a relatively labile constituent of soil organic matter (Jenkinson and Ladd, 1981) and is a key site for mineralization of organic P in soil. Soil microorganisms play a critical role in mineralization of organic inputs and partitioning of P into various organic fractions and likely provide continuous inputs of orthophosphate into the soil solution during the growing season. The addition of organic residues will provide a source of C and stimulate biological activity. Organic amendments can be a source of inorganic and organic P with the latter being subject to mineralization which releases inorganic P or forms other organic P fractions.

Soil biological activity controls the turnover of P by decomposition of organic P. Microorganisms produce a variety of enzymes capable of mineralising organic P (Cosgrove, 1977). Biomass P is an important dynamic P pool that forms 1 to 2 % of the total soil P (Stevenson, 1986). This has been found to be directly correlated with biomass C (Brookes *et al.*, 1984), inputs to soil which release inorganic phosphate or forms organic P fractions, immobilization of P in viable cellular biomass and solubilization of insoluble mineral P forms through release of organic acids.

2.3.3 Sequential phosphorus extraction procedure

2.3.3.1 The Hedley sequential P extraction procedure

The sequential P extraction method of Hedley *et al.* (1982) estimates inorganic and organic P fractions by applying increasingly harsher treatments to extract P pools believed to be increasingly less available to plants. This method has been used in the study of distribution, forms and transformation of P as a function of pedogenesis (Tiessen *et al.*, 1984; Sharpley *et al.*, 1987; Frossard *et al.*, 1989), in soil fertility evaluation (Tiessen *et al.*, 1983; Condron and Goh, 1989), in P dynamics of natural and cultivated systems (Hedley *et al.*, 1982; Trassar-Cepeda *et al.*, 1987) as well as in the influence of soil texture on distribution of soil P (O'Halloram *et al.*, 1987).

The sequential extraction procedures and modifications thereof stem from the work of Chang and Jackson (1957). The Hedley procedure is widely used in the study of transformations of applied phosphate (Nurwakera, 1991), in soil genesis studies and in determining the forms of native phosphate (Williams *et al.*, 1967; Peterson and Corey, 1966).

The Pi forms extracted in this procedure are: (i) resin extractable Pi which is the readily available P in equilibrium with soil solution, and some dissolved from reactive PRs; (ii) the sodium bicarbonate Pi associated with the surfaces of sesquioxides or carbonates (Mattingly, 1975); (iii) sodium hydroxide extracts P strongly bound to Al compounds (Williams *et al.,* 1980); (iv) and HCl extracts Ca-bound Pi, including primary mineral P (Williams *et al.*, 1971). Organic P in these extracts range from easily mineralizable Po in the anion exchange resin and $NaHCO_3$ extracts (Browman and Cole, 1978) to the more stable Po forms in the NaOH extract.

Several authors have found a positive correlation between values for labile P in the Hedley fractionation and the inorganic phosphorous extracted by other methods. Tiessen *et al.* (1984), Schlesinger *et al.* (1989), and Sharpley *et al.* (1987) found correlations between the Hedley resin and the labile Olsen P in alkaline soils and Bray-1 P in highly weathered soils. Trasar-Cepeda *et al.* (1987) found a strong correlation between values for inorganic P extracted with the Hedley method and values obtained following Chang and Jackson (1957) procedure.

Though the Hedley fractionation method has been successfully used in temperate soils, mainly on Mollisols, data on other soil orders especially Oxisols and Ultisols are limited to a few studies (Cross and Schlesinger, 1995). The use of this method to estimate P pools in field experiments of fertilized production systems can, therefore, provide the opportunity to understand the dynamics of soil P pools in the highly weathered soils such as the Oxisols of western Kenya. The choice of this method over others is that the same soil sample is sequentially treated with various reagents and by so doing the various proportions of the labile and non-labile phosphorus of differing plant availability can easily be established.

2.4 Phosphorus sorption by soils

Phosphorus sorption by the soil has been defined by Sanchez (1976) as the removal of soluble phosphate from solution by a soil or soil constituent followed by its concentration in the solid phase. Sorption of P occurs mainly on hydrous oxides of Fe and Al and at the surface of layer silicate clay particles (Frossard *et al.*, 1995) which increases in importance in soils with increasing weathering and clay content (Sanchez and Uehara, 1980). It is a dominant process controlling P availability in Ultisols and Oxisols with medium to fine textured topsoils (Sanchez and Uehara, 1980). Studies have shown that P sorption is influenced by soil properties such as pH, CEC (Hue, 1992), P status of the soil (Sanchez, 1976), clay content (Sanchez and Uehara, 1980), type of clay minerals and organic matter (Iyamuremye, 1996), temperature and time of reaction (Moshi *et al.*, 1974).

Sorption of P is a problem in many tropical soils, because of large quantities of hydrous Fe and Al oxides and 1:1 clays present in many highly weathered soils (Sanchez and Uehara, 1980). The large contents of Al and Fe oxides result from a long history of weathering. These oxides carry positive charges at pH values below 5 (Brady and Weil, 1996). In addition, kaolin, which is the prevalent clay mineral in many tropical soils carries positive charges thus enhancing the sorption capacity of these soils (Moshi *et al.*, 1974).

Phosphorus forms relatively insoluble compounds with Fe^{3+} and Al^{3+} at low pH, somewhat more soluble compounds with Ca^{2+} and Mg^{2+} at pH values near neutrality and sparingly soluble compounds at high pH values. There is a wide range of solubility of these compounds and their availability to crops is usually greatest within the pH range of 6 to 7 for most agricultural soils (Tisdale, 1985).

To some degree, the above P fixing soil components are distributed among soils and is related to soil taxonomy. Vertisols and Mollisols generally are dominated by 2:1 clays and have low P fixation capacities. Iron and Al oxides are prominent in Ultisols and Oxisols and cause higher P fixation capacity in these soils. Andisols, characterized by large quantities of amorphous oxides and allophane have the greatest P fixing capacity, and their productivity is often limited by this property.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Site and soil descriptions

The experiment was conducted at two sites: Nyabeda in Siaya district and Khwisero in Kakamega district of western Kenya. Mean annual rainfall for the two sites is 1800 mm occurring in two seasons: March - July (long rains) and September - January (short rains). Typical vegetation on the farms includes *Euphorbia tirucalli*, *Markhamia lutea*, *Cupressus lusitanica* and *Eucalyptus saligna* established as either woodlots or boundary plantings. Population density averages 1000 persons km^{-2}. The main agricultural activities include growing of maize, beans, bananas, and sorghum for subsistence, while sugarcane is grown as a cash crop. Livestock production is a common practice.

Table 1: Chemical and physical characteristics of the soils from the two sites

Character	Nyabeda	Khwisero
pH (1:2.5 soil: water)	5.4	5.2
Exchangeable acidity (cmol$_c$ kg^{-1})	0.3	1.0
Organic carbon %	1.58	1.75
Exchangeable Ca (cmol$_c$ kg^{-1})	4.65	3.53
Exchangeable Mg (cmol$_c$ kg^{-1})	1.90	1.25
Exchangeable K (cmol$_c$ kg^{-1})	0.09	0.07
Bicarbonate-EDTA extractable P (mg kg^{-1})	0.9	1.2
Clay (%)	55	35
Sand (%)	25	45
Silt (%)	20	20
Textural class	Clay loam	Sandy clay loam
P sorption at P conc. Of 0.2 mg P L^{-1}	316	375

The soil at the Nyabeda site was an Oxisol while at the Khwisero site the soil was an Alfisol. At the Nyabeda site, the soil was well-drained, very deep, dark reddish to yellowish red, friable to firm with humic topsoil. The chemical and physical characteristics of the two sites are presented in table 1. On both sites the soils had no physical or chemical barriers to rooting in the top 4 m.

3.2 Field Methods

3.2.1 Experimental set-up, treatments and rationale

The experiment comprising of 14 treatments (Table 2) was established in March 1997. Treatments where urea was applied (2, 3, 4 and 5) were compared with treatment where tithonia was applied (8, 9, 10 and 11) for interaction between N sources and P rates. An absolute control (treatment 13) was included for comparison with others as a test of improved performance due to inputs. The plot size was 6 m by 6 m. The experiment was laid out in a randomized complete block design (RCBD) replicated four times.

Table 2: Treatments and their description

TRT No	P Source	N Source	N Timing	P Timing	Placement Method	N Rate	P Rate	K Rate
1	No P	Urea	*Seasonal	-	-	60	0	56
2	TSP	Urea	*Seasonal	*Annual	Broadcast	60	50	56
3	MPR	Urea	*Seasonal	*Annual	Broadcast	60	50	56
4	TSP	Urea	*Seasonal	*One time	Broadcast	60	250	56
5	MPR	Urea	*Seasonal	*One time	Broadcast	60	250	56
6	TSP	Urea	*Seasonal	*Seasonal	Seed placed	60	20	56
7		Tithonia	*Seasonal	-	-	60	5.6	0
8	TSP	Tithonia	*Seasonal	*Annual	Broadcast	60	50	0
9	MPR	Tithonia	*Seasonal	*Annual	Broadcast	60	50	0
10	TSP	Tithonia	*Seasonal	*One time	Broadcast	60	250	0
11	MPR	Tithonia	*Seasonal	*One time	Broadcast	60	250	0
12	TSP	Tithonia	*Seasonal	*Seasonal	Seed placed	60	20	0
13	No P	No N	-	-	-	0	0	0
14	TSP	Urea	*Seasonal	*Seasonal	Broadcast	60	5.6	56

* One time means that the treatment was applied only once (beginning of the study). Annual means the treatment was applied once a year. Seasonal means that the treatment was applied in every cropping season.

3.2.2 Experimental management

The experiment was run for two cropping seasons (March – August 1997 and September 1997 – February 1998). In both seasons a sole maize crop (hybrid 511) was planted at a spacing of 0.75 m by 0.25 m. The maize seeds were sown at the rate of 2 per hole at the start of the rainy season and later thinned to 1 plant per hole to give a population of 53,300 plants ha^{-1}. Urea was split applied, half at planting and the other half at 5 weeks after planting (kneel height). The TSP and MPR at 250 kg P ha^{-1} were only applied at the start of the study (March, 1997) while the 50 kg P ha^{-1} rate was applied annually i.e. in March, 1997 and 1998. Triple superphosphate was broadcast as granules. Minjingu phosphate rock was broadcast as finely ground powder (>90% passing 100 mesh sieve). Both were incorporated by hand hoes to approximately 15-cm depth at planting. Finely chopped green biomass loppings of tithonia (approximately 1-2 cm) were broadcast and incorporated at planting to the 15 cm soil depth together with the P source and rates described above.

3.2.3 Soil Sampling

Edelman soil augers were used to obtain surface soil samples at (0 –15 cm). For each experimental plot a composite sample was collected from nine sampling points, mixed and sub-sampled for the analysis of physical and chemical properties. Soil sampling was done twice. Soil samples collected immediately after harvest (September, 1997 and February, 1998) were used for the analysis of soil P fractions. Soil samples collected two weeks after application of the fertilizers in each season were used for microbial C and P determination.

3.2.4 Assessment of maize yield

Harvesting was done by leaving out the outer two rows on both sides of the plots and the outer two plants at the end of each plot in each of the remaining rows to minimize edge effect and thus giving a net harvest area 22.5 m^2. Cobs were removed from the husks in the standing crop. The cobs from each plot were placed in labelled paper bags and their total fresh weight taken. The cobs were arranged into different classes (large, medium and small) and a sub-sample was picked proportionately from each size class. Fresh weight of each sub-sample was taken and then placed in pre-labelled paper bags. The sub-samples were then oven dried at 60°C to constant weight.

3.3 Phosphorus extraction methods

3.3.1 Soil phosphorus determination methods (non-sequential procedures)

3.3.1.1 Resin extractable inorganic phosphorus

Resin extractable P was determined by the method of Sibbesen (1978) in which 2.5 g of soil was shaken for 16 hours at 175 rpm with 40 mL of deionized water and a mesh bag containing 1 g Dowex 1 - X 8 anion exchange resin in HCO_3^- form. Phosphorus adsorbed by the resin was recovered using 20 mL of 0.5M HCl by shaking for 1 hr at 175 rpm and filtering through Whatman No. 5 filter paper. Phosphorus in solution was analyzed colorimetrically by the molybdate blue method of Murphy and Riley (1962).

3.3.1.2 Bicarbonate extractable inorganic and organic phosphorus

Bicarbonate extractable P was determined by shaking 2.5 g of air-dried soil with 50 mL of 0.5 M $NaHCO_3$ (pH 8.5) for 30 minutes at 150 rpm (Olsen and Sommers, 1982). Inorganic P was determined colorimetrically by the molybdate blue method. Total P in the extract was determined after digestion with ammonium persulphate in an autoclave for 1 hr at 121°C and 15 Pascals. Bicarbonate extractable organic P (Po) was calculated as the difference between the total P (Pt) and the inorganic P (Pi) in the extract.

3.3.1.3 Extractable inorganic phosphorus using modified Olsen extractant

Modified Olsen P was determined using 2.5 g soil (<2 mm) and 25 mL of 0.5 M $NaHCO_3$ + 0.01 M ethylene diamine tetra-acetic acid disodium salt (disodium

EDTA) at pH 8.5 by stirring on a paddle-type stirrer for 10 minutes, then filtering through Whatman No. 5 filter paper into clean 60 mL extraction bottles. Inorganic P in the extract was determined colorimetrically by the molybdate blue method of Murphy and Riley (1962).

3.3.2 Soil P determination by sequential-P extraction procedure

The method that was used to sequentially fractionate soil P is the modified version of the Hedley *et al.* (1982) procedure schematically presented in appendix 1. The various P fractions were extracted from a 0.5 g soil sample by applying a series of increasingly reactive reactants to initially remove labile inorganic and organic P pools followed by more stable Pi and Po forms removed by stronger extractants.

On the first day, 0.5 g of soil was weighed into 50 mL centrifuge tubes. Into each tube, one anion exchange resin bag and 30 mL of deionised water were added and shaken for 16 hours (overnight). On the second day, the resin bags were removed from the centrifuge tubes and soil washed back into the tubes. The resin bags were then placed in clean 50 mL extraction bottles and 20 mL of 0.5M HCl added. This was shaken at 175 rpm for one hour.

Phosphorus was determined using the molybdate blue method. The soil suspension in the centrifuge tubes was centrifuged at 7000 rpm for 10 minutes at room temperature. Water was decanted and 30 mL of Olsen extractant (0.5 M $NaHCO_3$ pH 8.5) was added. The suspension was shaken overnight. On the third day, the soil suspension was centrifuged at 7000 rpm for 10 minutes. The $NaHCO_3$ extract was decanted into extraction bottles. Inorganic phosphorus (Pi) and total P (Pt) were determined in the extract. Total P (Pt) in the extract was determined after digestion of 1 mL of the extract with 1 mL 10% ammonium persulphate in an autoclave for 1 hour. After cooling, 1 drop of 0.25% p-nitrophenol was added. This was followed by the dropwise addition of sufficient 5 M NaOH to just make the extract alkaline (Yellow colour). Then 1.2M H_2SO_4 was added dropwise until the yellow colour just disappeared.

Extractable organic P (Po) was calculated as the difference between total P (Pt) and inorganic P (Pi) in the extract. Into the soil suspension in the centrifuge tubes, 30 mL of 0.1N NaOH was added. The suspension was shaken overnight. On the fourth day, the soil suspension was centrifuged at 7000 rpm for 10 minutes. Sodium hydroxide extract was decanted into extraction bottles. From this extract, 5 mL of the of the decanted extract was acidified with 0.6 mL of 1.2M H_2SO_4 to pH 1.5 and centrifuged for 10 minutes at 7000 rpm to precipitate the dissolved organic compounds. After that 2 mL of the supernatant was analysed for Pi by the molybdate blue Murphy Riley method. Total P (Pt) was determined as outlined for $NaHCO_3$ extract.

Extractable organic P (Po) was calculated as the difference between total P (Pt) and inorganic P (Pi) in the extract. Into the soil suspension in the centrifuge tubes, 30 mL of 1M HCl was added. This suspension was shaken overnight. On the fifth day, the soil suspension was filtered through Whatman No. 5 filter paper. From this extract, Pi was determined by the molybdate blue method. The soil residue in the centrifuge tube was discarded.

3.3.3 Soil microbial biomass phosphorus and carbon

In the determination of soil microbial biomass air dry soils were used. Soil samples at 60% water filled pore space were incubated in a dark place at 25°C for 7 days for respiration to stabilize.

Soil microbial biomass P was determined on the pre-incubated soils using the procedure of Kuono *et al.* (1995). Three sets of 2 g of moist equilibrated soil and four anion resin exchange membranes (AEM) were shaken end to end for 16 hours at 175 rpm. The first set contained 30 mL of deionized water. The second set contained 30 mL of a P standard (1.0 mg PL^{-1}) spike solution to estimate the recovery of $CHCl_3$ released P. The third set contained 30 mL of deionized water and 2 mL of $CHCl_3$. The P adsorbed by the anion exchange membranes (2.5 by 2.5 cm) was eluted with 20 ml of 0.5M HCl and determined colorimetrically by the molybdate blue method. Chloroform released P was calculated as the difference between the fumigated (where $CHCl_3$ was applied) and non-fumigated (where $CHCl_3$ was not applied) sample concentration. All results are based on the means of two laboratory replicates.

Microbial biomass carbon was determined using the pre-incubated soils. Samples of 25 g moist equilibrated soils were weighed into two sets of bottles. In the first set soluble carbon was extracted using 100 mL of 0.5M K_2SO_4. This was done by shaking at 150-rpm for one hour followed by filtration. The second set of bottles was $CHCl_3$ fumigated by placing the glass bottles containing soil samples in a vacuum dessicator containing 50 ml alcohol free $CHCl_3$. Five water saturated filter papers (Whatman No. 1) were placed inside the vacuum dessicator to keep the samples moist. The lid of the dessicator was closed and a vacuum was applied using a vacuum pump until the $CHCl_3$ started to boil. The tap of the dessicator was closed and the samples were incubated in a dark room for 24 hours. After a day of incubation, the dessicator was opened to allow the chloroform to dissipate. The fumigated soil samples were then transferred into 125 mL polythene bottles. Extraction was done using 100 mL of 0.5M K_2S0_4.

Carbon concentration in both cases was determined using the procedure of Anderson and Ingram (1993), by oxidizing with K_2CrO_7 and concentrated sulphuric acid at 150° C for 30 minutes, followed by colortimetric determination of Cr^{3+}, and compared with sucrose standards digested in the same manner.

Microbial biomass C = (C fumigated - C non-fumigated)

3.3.4 Phosphorus sorption capacity

Phosphorus sorption capacity of the soils was determined using the method of Fox and Kamprath (1970). Three grams of soil plus 30 mL of different P standards (0, 100, 200, 300, 400, 500 and 600 mg P kg $^{-1}$) prepared in 0.01 M $CaCl_2$ and two drops of toluene (to retard microbial activity) were shaken for 30 minutes twice a day for 6 days at 150 rpm. At day six, the samples were filtered and analysed colorimetrically for P. Phosphorus sorbed was calculated as the difference between P added and the final P in soil solution. P sorbed at 0.2 mg P L^{-1} in solution (q in mg P kg $^{-1}$ soil) was obtained for the two sites using the Langmuir equation as described by Fox and Kamprath (1970):

$$C/(x/m) = 1/[(K*b) + (C/b)]$$

Where C = final supernatant solution P concentration (0.2 mg P L^{-1}), x/m = P sorbed per unit soil mass (mg P kg^{-1} soil); b = adsorption maximum (mg Pg^{-1} soil); K = a constant related to the adsorption energy of the soil for phosphorus (adsorption affinity L mg $^{-1}$).

3.3.5 Statistical analysis

Genstat 5 for Windows (Release 3.2) (Lane *et al.*, 1987) computer package was used for statistical analysis of soil P fractions and maize yield data. Analysis of variance (ANOVA) was conducted to determine the effects of treatments on the soil P fractions. Least significant differences (LSD) at P=0.05 were used to separate significant differences among treatments. LSD was approximated as SED x 2.0 or 2.8 (at the 0.05 and 0.01significance levels) respectively. Linear regression was used to determine the relationship between maize yield and P fractions.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Effect of treatments on sequentially extractable soil P pools at the two sites

Phosphorus applied at the higher rate of 250 kg P ha^{-1} as either MPR or TSP gave significantly higher ($P \leq 0.01$) extractable inorganic P pools (RP-Pi, $NaHCO_3$-Pi and NaOH-Pi) than the lower rate of 50 and 0 kg P ha^{-1} in both seasons for Nyabeda (clay loam) (Tables 3 and 5) and Khwisero (sandy clay loam)(Tables 4 and 6) respectively. P treatment x N source interactions were not significant for all the inorganic P fractions during the experimental duration of two cropping seasons (Appendices 2-5).

The significant increase above the control of the 250 kg P ha^{-1} application rate in extractable levels of all the inorganic P (Pi) fractions at the end of season 1 and 2 (Tables 3,4,5 and 6) indicates that quantities of extractable Pi are dependent on the rate of P application. The enrichment of all the inorganic P fractions indicates that there was an increase in both the liquid and the reserve capital inorganic P (Baanante, 1997). The enrichment of especially the labile Pi pools at the higher rate suggests that the inorganic P fertilization had been in excess of crop requirement which is consistent with the observations of Hellums *et al.* (1992) and Schmidt *et al.* (1996). The low extractable Pi fractions from the 50 kg P ha^{-1} rate indicate that the low P rate could not fully mitigate P deficiency in these high P sorbing soils. Phosphorus from the lower rates could have gone into building the reserve capital and not the liquid capital P (Buresh *et al.*, 1997).

Table 3: Sequentially extractable soil P fractions at Nyabeda (clay loam) end of season 1

	Soil P pools (kg ha^{-1})											
	RP-Pi		NaHCO$_3$-Pi		NaOH-Pi		HCl-Pi		NaHCO$_3$-Po		NaOH-Po	
P treat	T	U	T	U	T	U	T	U	T	U	T	U
Control	5.2	5.6	8.5	8.5	75	81	9.2	11	44	47	274	309
50 TSP	8.6	6.9	9.6	9.5	77	85	9.7	9.7	44	47	268	291
50 PR	7.2	6.2	9.8	8.4	84	76	9.6	8.2	45	43	275	285
250 TSP	27	27	19	27	125	143	10	12	47	46	299	281
250 PR	26	28	16	14	103	99	12	11	44	43	268	288
SED P	3.6		1.5		7.1		0.44		2.1		9.1	
SED N	2.6		1.1		5.0		0.31		1.5		6.4	
SED PxN	5.1		2.1		10		0.63		2.9		13	

T= tithonia, U= urea, SED= standard error of difference in means, LSD =SED * T (at specified significance level)

Table 4: Sequentially extractable soil P fractions at Khwisero (sandy clay loam) end of season 1

	Soil P pools (kg ha^{-1})											
	RP-Pi		NaHCO$_3$-Pi		NaOH-Pi		HCl-Pi		NaHCO$_3$-Po		NaOH-Po	
P treat	T	U	T	U	T	U	T	U	T	U	T	U
Control	7.4	8.4	7.7	7.4	72	72	10	9.4	56	57	368	322
50 TSP	15	11	11	9.2	84	74	10	10	57	52	329	327
50 PR	12	11	7.9	8.8	71	71	11	11	52	52	327	328
250 TSP	56	43	29	25	135	116	13	12	60	57	354	356
250 PR	42	39	16	16	101	109	21	21	54	58	337	345
SED P	4.7		2.0		7.8		1.1		2.4		13	
SED N	3.3		1.4		5.6		0.77		1.7		9	
SED PxN	6.6		2.8		11		1.5		3.4		19	

T = tithonia, U = urea, SED= standard error of difference in means, LSD =SED * T (at specified significance level)

On the other hand, it was observed that extractable RP-Pi from MPR-treated soils was significantly higher ($P \leq 0.01$) than that from TSP-treated soils at the Nyabeda (clay loam) site in season 2 (Table 5). This may be explained by the differences in the rates of dissolution of the two sources of P and the subsequent reactions of their dissolution products with the soil components. Water-soluble Pi from PRs is known to improve with time due to the slow but steady influx of P from the dissolution of PR material (Khasawneh and Doll, 1978; Rajan *et al.*, 1996). This gradual dissolution may explain the increase in this fraction (RP-Pi) from MPR with time. The Undissolved PR is thought to represent capital P that can supply liquid P within 10 years (Buresh *et al.*, 1997). Most of the soil solution P (RP-Pi) from TSP-treated soils at Nyabeda is likely to have reacted with soil components and quickly converted to other Pi forms such as $NaHCO_3$-Pi and NaOH-Pi. Highly weathered acidic Oxisols with high clay contents as those from Nyabeda site are presumably associated with large quantities of hydrous Al and Fe oxides (Sanchez and Uehara, 1980). This being the case therefore, it is possible that most of the soil solution P from TSP treated soils at this site may have gone into the NaOH extractable fraction as evidenced by the increase in net extractable NaOH-Pi in season 2 (Figure 2).

In contrast, although not significant TSP-treated soils had higher extractable RP-Pi than MPR-treated soils at Khwisero (sandy clay loam) in the two seasons (Tables 4 and 6). This may be attributed to possibly lower rate of dissolution of MPR possibly because of the lower clay and presumably lower Al and Fe components at the Khwisero site. The higher values of RP-Pi from TSP-treated soils imply that the rate of conversion of RP-Pi to other Pi fractions ($NaHCO_3$-Pi and NaOH-Pi) was slower at the Khwisero site. It also indicates that the Khwisero site, had fewer P sorbing sites and hence the higher extractable P from TSP treated soil in soil solution.

Table 5: Sequentially extractable soil P fractions at Nyabeda end of season 2

	Soil P pools (kg ha^{-1})											
	RP-Pi		$NaHCO_3$-Pi		NaOH-Pi		HCl-Pi		$NaHCO_3$-Po		NaOH-Po	
P treat	T	U	T	U	T	U	T	U	T	U	T	U
Control	7.1	5.2	9.2	9.6	79	77	10	11	45	44	327	308
50 TSP	8.1	9.8	10	11	84	91	8.5	9	44	46	317	324
50 PR	9.6	9.0	10	10	93	85	10	10	43	41	324	322
250 TSP	28	20	23	21	143	135	10	11	44	44	337	333
250 PR	42	33	19	17	127	116	12	11	45	43	320	313
SED P	2.2		1.2		5.0		0.97		1.6		8.9	
SED N	1.6		0.84		3.5		0.69		1.1		6.4	
SED PxN	3.2		1.7		7.1		1.4		2.2		13	

T = tithonia, U = urea, SED = standard error of difference in means means LSD =SED * T (at specified significance level)

Table 6: Sequentially extractable soil P fractions at Khwisero end of season 2

	Soil P pools (kg ha^{-1})											
	RP-Pi		NaHCO$_3$-Pi		NaOH-Pi		HCl-Pi		NaHCO$_3$-Po		NaOH-Po	
P treat	T	U	T	U	T	U	T	U	T	U	T	U
Control	15	10	13	10	85	85	11	10	82	59	284	297
50 TSP	17	15	12	12	103	93	10	10	58	63	298	295
50 PR	20	17	15	10	116	101	13	10	60	54	283	307
250 TSP	59	46	38	30	165	158	15	13	78	76	300	288
250 PR	44	46	24	23	145	134	24	20	67	62	294	293
SED P	4.6		2.2		9.2		1.5		7.2		11	
SED N	3.2		1.6		6.5		1.1		5.3		7.7	
SED PxN	6.5		3.2		13		2.1		11		15	

T= tithonia, U = urea, SED = standard error of difference in means means LSD =SED * T (at specified significance level)

Net extractable (difference from the control) RP-Pi from the two P sources in the sandy clay loam was higher than that from the clay loam site in both seasons (Figures 1and 2). The observed differences are attributed to differences in site characteristics. The higher extractable soil solution Pi (RP-Pi) from sandy clay loam site could be attributed to slower conversion to the less labile Pi fractions. This is possibly due to the lower clay content at this site as opposed to the higher clay content on the clay loam site that may have led to the conversion of soil solution to other Pi fractions (NaHCO$_3$-Pi and NaOH-Pi). Decrease in net extractable RP-Pi from TSP with time in the two sites (Figure 2) could be explained by the fact that a large proportion of this fraction is plant available and, therefore, could have been taken up by the maize crop, soil biota or converted to the NaHCO$_3$-Pi and NaOH-Pi by chemical immobilization. In contrast an increase in RP-Pi from MPR with time at both sites (Tables 5 and 6) is mainly a result of a slow but steady influx of P from dissolution of MPR fertilizer by the soil components and the resin.

Extractable RP-Pi from TSP + tithonia was significantly higher ($P \leq 0.01$) than that from TSP + urea at Khwisero in both seasons (Tables 4 and 6) and at Nyabeda in season 2 (Table 5). This may be attributable to the fact that tithonia on decomposing releases organic acids and other by-products which compete for the P sorbing sites. In turn orthophosphate can affect P sorption capacity of the soils by blocking the P sorption sites (Nziguheba *et al.*, 1998).

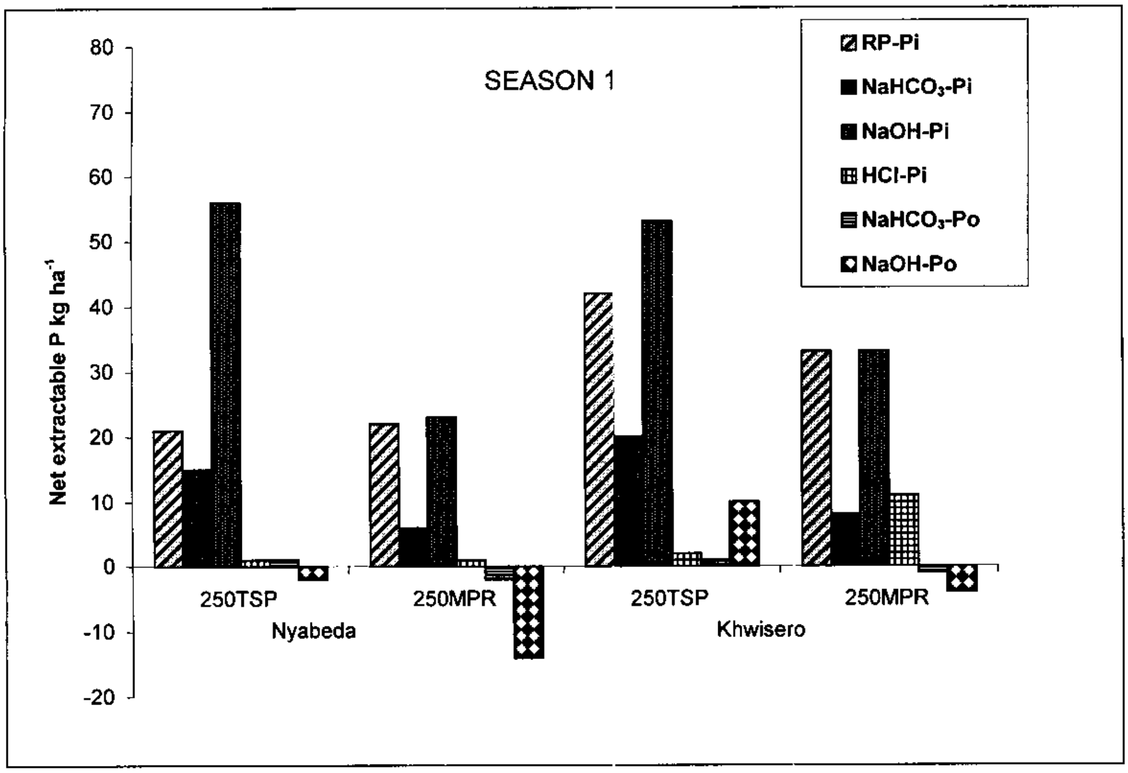


Figure1: Net (difference from the control) sequentially extractable P fractions from 250 kg P ha^{-1} at the end of season 1

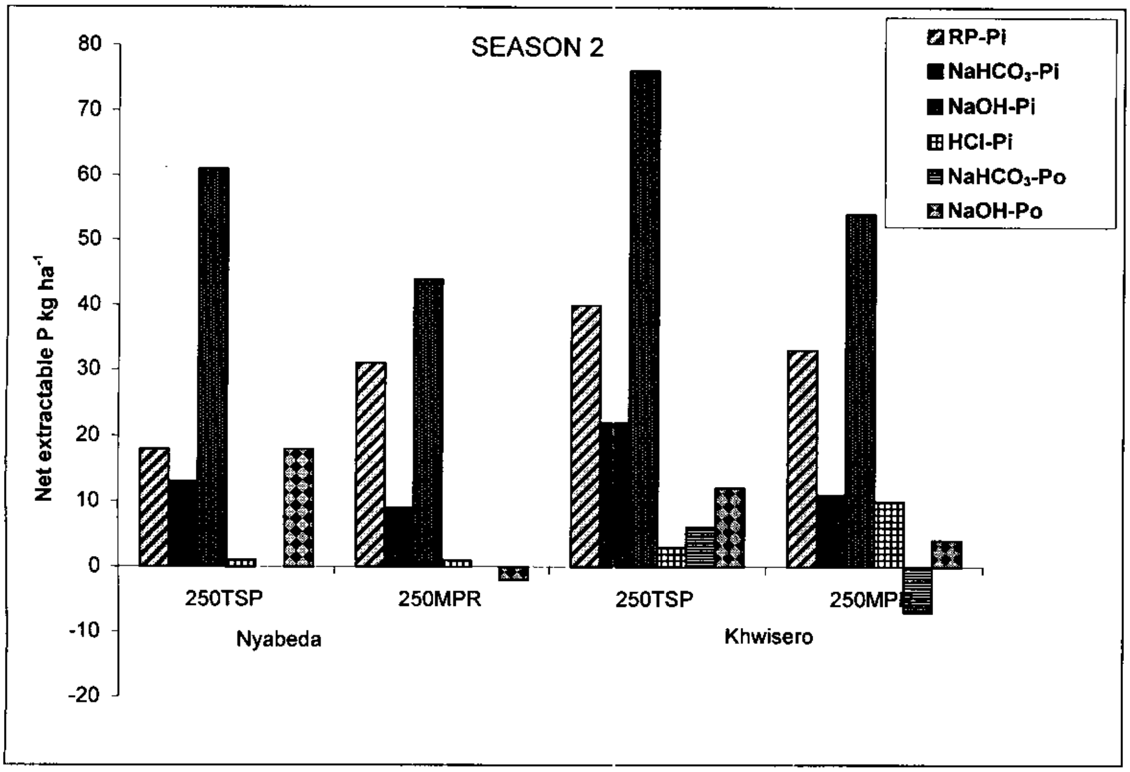
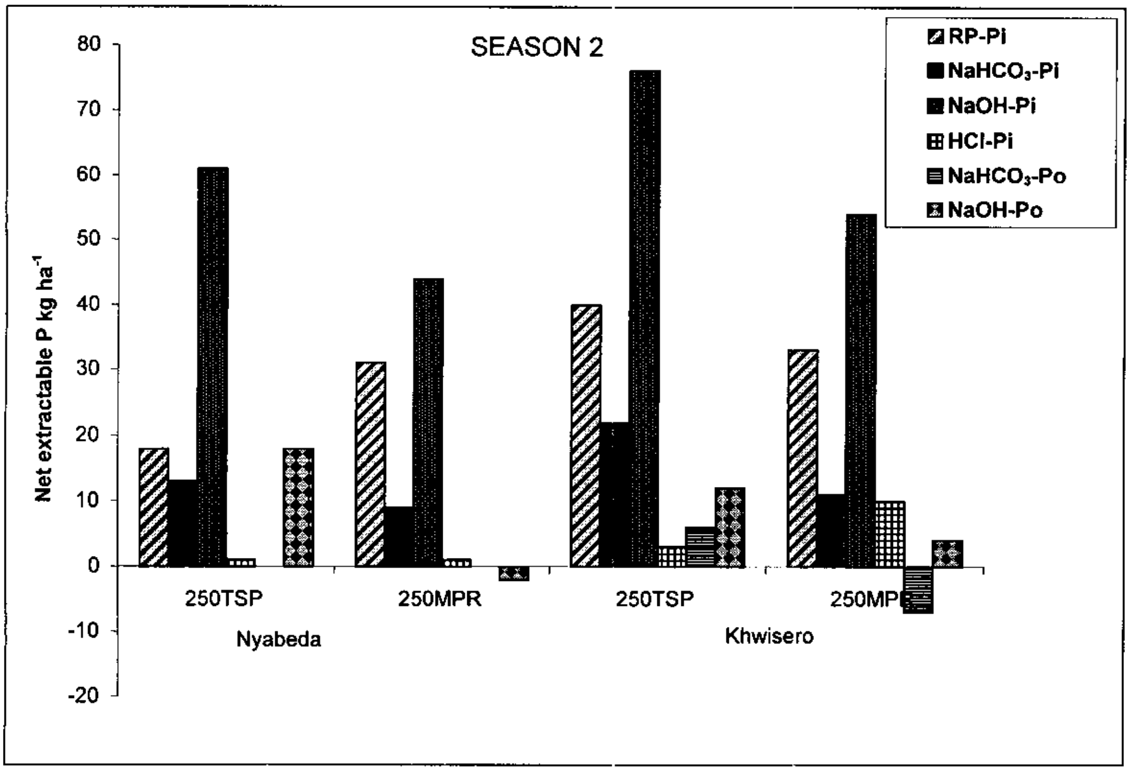


Figure 2: Net (difference from the control) sequentially extractable P fractions from 250 kg P ha^{-1} at the end of season 2

Net extractable $NaHCO_3$-Pi from TSP-treated soil was higher than that from MPR-treated soil at the two sites in both seasons (Figures 1 and 2). This could be attributed to the differences in the dissolution rates and amounts of residual products from these two sources of P. It does indicate that more P from TSP dissolved and was in the $NaHCO_3$-Pi form. $NaHCO_3$-Pi is supposedly a Pi form loosely sorbed on surfaces of sesquioxides and carbonates (Mattingly, 1975). The net positive extractable $NaHCO_3$-Pi indicates that inorganic P fertilizers were applied in excess of plant uptake and therefore this fraction formed a sink for inorganic P fertilizers in these soils. The higher net extractable $NaHCO_3$-Pi from TSP-treated soils from the sandy clay loam as compared to clay loam in both seasons (Figures 1 and 2) indicates that more Pi was loosely bound to soil particles at the sandy clay loam site. It is possible that the clay loam site having more clay (Table 1) and presumably higher Fe and Al contents, most of the $NaHCO_3$-Pi could have been converted to the NaOH-Pi



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Extractable NaOH-Pi from TSP-treated soil was significantly higher ($P \leq 0.05$) than that from MPR-treated soil at the two sites in both seasons (Tables 3-6). This indicates that more P from TSP as compared to P from MPR dissolved and was strongly sorbed onto soil colloids (Al and Fe oxides). NaOH-Pi is supposedly a Pi form strongly adsorbed to the surfaces of crystalline and non-crystalline Al and Fe oxides (Williams *et al.*, 1980). The difference in the dissolution rates and therefore amounts of residual products from these two P sources may be the main cause for the differences observed in extractable NaOH-Pi between the two sources of P. While TSP is water-soluble and therefore dissolves completely in water, MPR is only sparingly soluble (about 1.9 % of the total P is readily water soluble according to Mutuo *et al.* (1999). This fraction is thought to form a major P sink in highly weathered soils (Beck, 1991). The net positive extractable NaOH-Pi from MPR-treated soils at the two sites (Figures 1 and 2) indicates that application of PRs classified as either medium or highly reactive (Hammond and Leon, 1983) can increase capital P as determined by NaOH in acid soils. Increases in NaOH-Pi from the same P source with time is certainly the result of the gradual dissolution of MPR and the conversion of the labile Pi forms (RP-Pi and $NaHCO_3$-Pi) to the moderately labile (NaOH-Pi) form. The relatively higher net extractable NaOH-Pi compared to other Pi fractions at the two sites reflects the importance of Fe- and Al-P in highly weathered soils (Sharpley *et al.*, 1987). The increase in net extractable NaOH-Pi from the two P sources at the two sites with time means that other Pi fractions especially the labile forms (RP-Pi and $NaHCO_3$-Pi) were converted to NaOH-Pi.

Despite the fact that $NaHCO_3$-Pi and NaOH-Pi are not completely separate pools particularly in acid soils, as they represent a continuum of Fe and Al associated-P extractable with increasing pH, extraction with alkaline 0.5M sodium bicarbonate (Olsen *et al.*, 1954) was much less effective than sodium hydroxide in removing phosphorus. Dilute sodium bicarbonate being a weak alkali displaces phosphorus from the surfaces of calcium, iron and aluminium (Jackson, 1958) and may, therefore, not be expected to extract as much phosphorus as sodium hydroxide which dissolves all the Fe- and Al-phosphate in the soil. At the other extreme 0.1 M sodium hydroxide was very effective in extracting both inorganic and organic phosphorus from the soils. This is in keeping with the expectation that the inorganic phosphorus in acid soils would be mainly in the form of Fe and Al phosphates (McLaughlin *et al.*, 1977; Ryden *et al.*, 1977). These forms are much more soluble in alkali than in water or acid solutions. The high amount of total phosphorus extractable with 0.1M sodium hydroxide is a reflection of the high amount of the organic phosphorus in these soils. Very often, organic phosphorus constitutes the major fraction of the total extractable phosphorus in highly leached tropical soils (Beck, 1991).

Extractable HCl-Pi from MPR-treated soil was significantly higher ($P \leq 0.01$) than that from TSP-treated soils in the sandy clay loam in both seasons (Tables 4 and 6). In contrast net extractable HCl-Pi from MPR-treated soils was observed to be similar to that from TSP-treated soils in both seasons in the clay loam site (Tables 3 and 5). The probable reason for this is that the higher clay and presumably Al and Fe contents in the clay loam site could have contributed to faster dissolution of MPR. The higher net extractable HCl-Pi from MPR-treated soils in the sandy clay loam site as compared to the clay loam in both seasons (Figures 1 and 2) indicates that a considerable amount of undissolved MPR in the form of Ca-P was still in the soil at the sandy clay loam site. This means that dissolution of MPR and the conversion of its dissolution products to other Pi fractions was slower at the sandy clay loam site. This is possibly because of the lower clay content at this site. The decrease in HCl-Pi from MPR-treated soils at the two sites with time is due to the dissolution of Ca-P by soil components and conversion to more labile Pi and Po forms.

The differences observed in the amounts of extractable P and available P derived from TSP and MPR highlight the marked difference in the reactions of these two P sources on coming in contact with the soil. The two sources of P have different solubilities in soil water and therefore leave different types and amounts of residual compounds in the soil (Kumar *et al.*, 1993; Menon and Chien, 1995). Soluble P fertilizer products are mostly sorbed by soil colloids while sparingly soluble PRs remain as Ca-P that dissolves gradually to the labile Pi forms. The differences observed between the two sites are attributed more to the differences in the amounts of clay and presumably Fe and Al oxide content than any other factor. The clay loam site with higher clay content and possibly more Al and Fe components (as confirmed by the dark reddish to yellowish red colour on site) may have contributed to faster rates of dissolution of MPR with most of the dissolution products going into the labile and moderately labile Pi fractions. The lower clay content in the sandy clay loam site could have contributed to slower rates of dissolution therefore more Ca-P being detected even after one year at this site. Highly weathered soils with higher clay contents are thought to have higher P sorbing capacities (Sanchez and Uehara, 1980).

Organic P fractions ($NaHCO_3$-Po and NaOH-Po) at the two sites were not significantly influenced by the P rate or P source during the experimental period

(Appendices 2-5). This implies that most of these two P pools were probably associated with stabilized soil organic matter. This is consistent with the results of an earlier study where addition of inorganic P sources to an Oxisol had no effect on NaOH-Po in one year (Mutuo *et al.*, 1999).

Net extractable $NaHCO_3$-Po from TSP-treated soil was slightly higher than that from MPR-treated soils at the two sites and seasons (Figures 1 and 2). This may be attributed to provision of adequate labile Pi from TSP for microbial growth leading to a general increase in soil organic forms. In MPR-treated soils, the lower rate of dissolution of this P source may have led to enhanced mineralization of soil organic forms to supply Pi for microbial activity.

Extractable NaOH-Po from MPR treated soils was observed to be lower than the control at the two sites (Figures 1 and 2). Decreases in Po concentration under inorganic P fertilization are at variance with the studies cited by Beck and Sanchez (1994) who found increases in extractable Po after a few months of inorganic P fertilization of Oxisols. The decrease in the Po pool can partly be explained by mineralization resulting from declines in soil organic matter (Agbenin and Goladi, 1997). In addition N and organic P fertilization probably provided the macronutrient substrate for rapid growth of microbial population, thus facilitating soil organic matter minerazation (Beck and Sanchez, 1994). There was a possibility of a temporary depletion of the labile Pi in the MPR-treated soils. Depletion of labile Pi lead to mineralization of organic P forms (Rajan *et al.*, 1996).

4.2 Effects of treatments on non-sequential extractable P pools from the two sites

Phosphorus applied at the higher rate of 250 kg P ha^{-1} as either MPR or TSP gave significantly higher ($P \leq 0.01$) extractable inorganic P pools (RP-Pi, $NaHCO_3$-Pi and ExP) than the lower rate of 50 and 0 kg P ha^{-1} in both seasons for Nyabeda (clay loam)(Tables 7 and 9) and Khwisero (sandy clay loam) (Tables 8 and 10). Extractable RP-Pi from MPR was significantly higher ($P \leq 0.01$) than from TSP in the clay loam site in season 2 (Table 9) in contrast RP-Pi, from TSP-treated soils in the sandy loam site was significantly higher ($P \leq 0.01$) than that from MPR-treated soils in season 2 (Table 10). The reasons for the differences in the amounts of extractable inorganic P fractions between the higher and lower rates of applied P and the contrasting observation in the amounts of extractable RP-Pi between the P sources at the two sites have been outlined above (section 4.1).

Table 7: Extractable P by non-sequential P test methods in Nyabeda at the end of season 1

Treatment	Soil P pools (kg ha^{-1})							
P treat	RP-Pi		$NaHCO_3$-Pi		ExP		$NaHCO_3$-Po	
	Tithonia	Urea	Tithonia	Urea	Tithonia	Urea	Tithonia	Urea
Control	3.9	4.1	4.0	3.8	1.4	1.3	26	26
50 TSP	6.8	6.9	5.2	4.8	2.2	1.8	25	25
50 MPR	9.6	6.4	4.8	3.9	1.9	1.6	25	24
250 TSP	32	34	18	21	7.2	12	26	25
250 MPR	38	44	8	7.7	4.1	3.3	25	25
SED P	4.0		1.6		0.64		2.0	
SED N	2.9		1.1		0.45		1.4	
SED P x N	5.7		2.3		0.91		2.8	

SED = standard error of difference in means, ExP = Modified Olsen P, LSD =SED * T (at specified significance level)

Table 8: Extractable P by non-sequential P test methods in Khwisero at the end of season 1

Treatment	Soil P pools (kg ha^{-1})							
P treat	RP-Pi		$NaHCO_3$-Pi		ExP		$NaHCO_3$-Po	
	Tithonia	Urea	Tithonia	Urea	Tithonia	Urea	Tithonia	Urea
Control	6.6	5.2	4.3	3.6	1.8	1.9	32	32
50 TSP	10	8.3	6.8	5.7	4.0	2.9	31	31
50 MPR	8.5	6.6	4.8	4.2	2.6	2.7	30	31
250 TSP	39	39	20	22	16	14	34	31
250 MPR	40	32	10	9.4	5.3	5.8	30	31
SED P	3.8		1.2		1.1		1.6	
SED N	2.7		0.86		0.78		1.1	
SED P x N	5.4		1.7		1.6		2.3	

SED = standard error of difference in means, ExP = Modified Olsen extractable P, LSD =SED * T (at specified significance level)

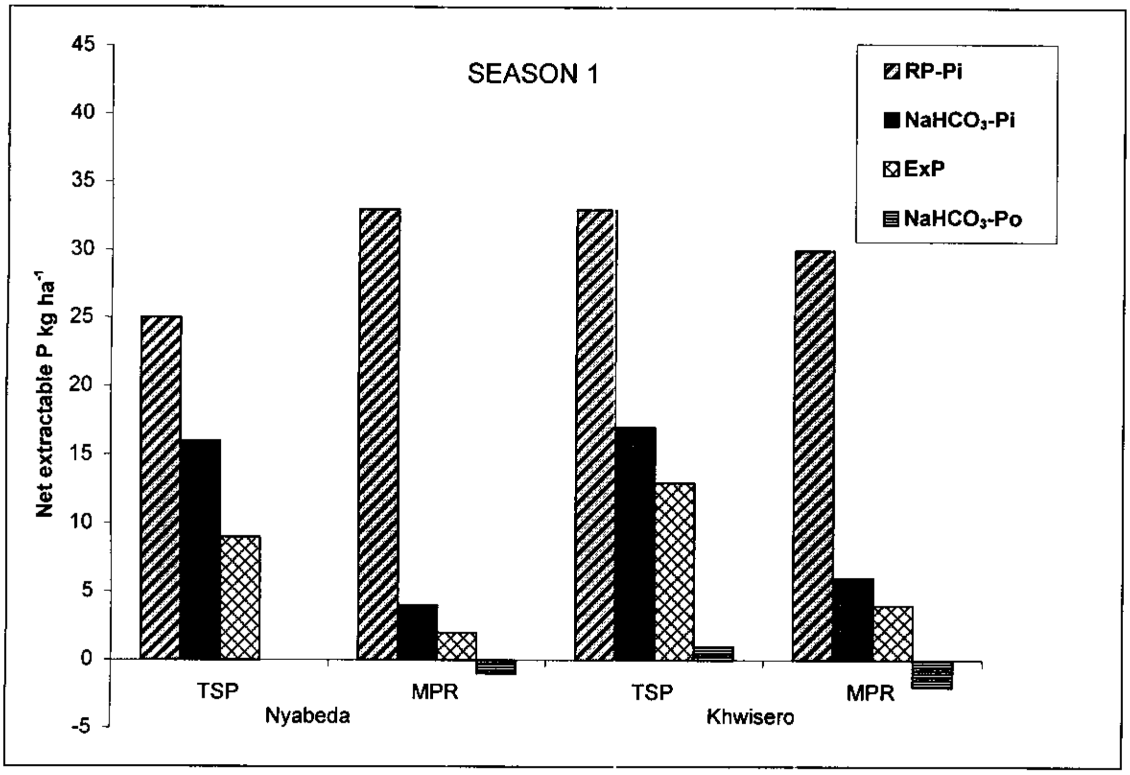


Figure3: Net (difference from the control) extractable P fractions from 250 kg P ha^{-1} at the end of season 1

Table 9: Extractable P by non-sequential P test methods in Nyabeda end of season 2

Treatment	Soil P pools (kg ha^{-1})							
P treat	RP-Pi		NaHCO$_3$-Pi		ExP		NaHCO$_3$-Po	
	Tithonia	Urea	Tithonia	Urea	Tithonia	Urea	Tithonia	Urea
Control	5.7	4.4	4.4	5.4	2.6	2.6	32	32
50 TSP	5.6	7.1	4.9	5.4	2.7	2.8	32	31
50 MPR	7.7	6.9	5.6	5.0	2.8	2.6	33	32
250 TSP	23	19	14	12	6.7	9.2	32	31
250 MPR	35	30	11	9.0	9.4	5.0	30	30
SED P	2.9		0.67		1.1		1.0	
SED N	2.1		0.47		0.81		0.75	
SED P x N	4.1		0.94		1.6		1.5	

SED = standard error of difference in means, ExP = Modified Olsen P, LSD =SED * T (at specified significance level)

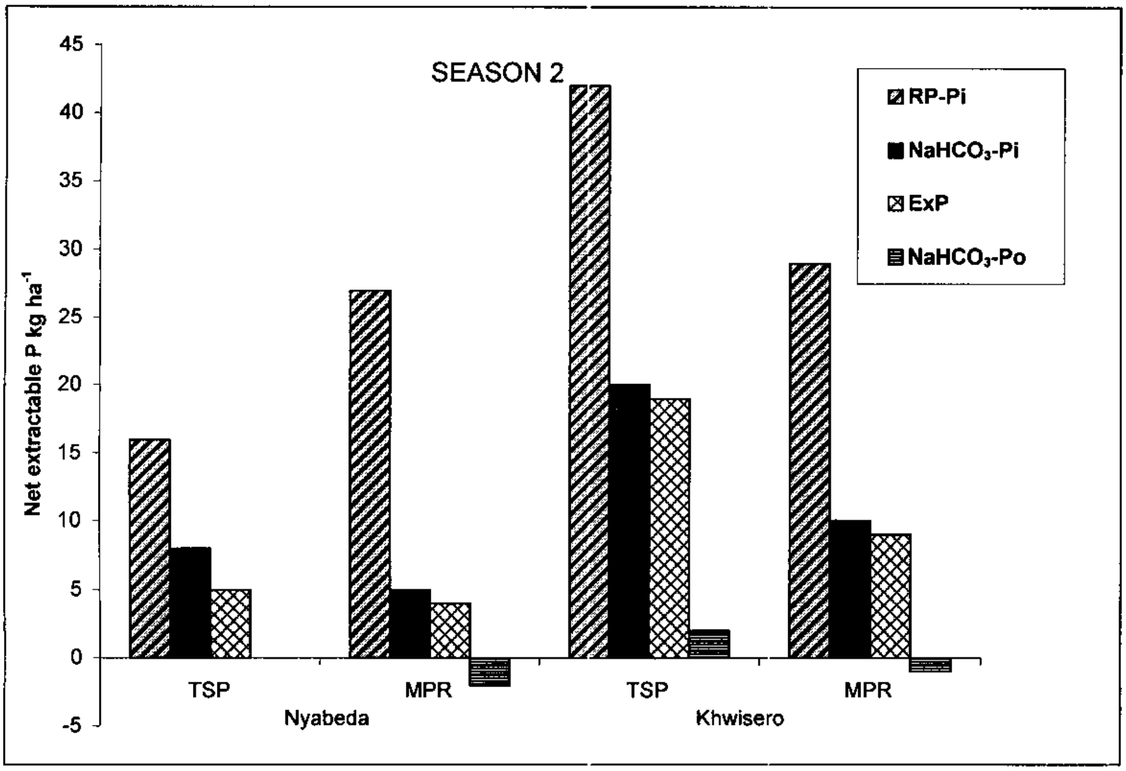


Figure 4: Net (difference from the control) non-sequential extractable P fractions from 250 kg P ha^{-1} at the end of season 2

Table 10: Extractable P by non-sequential P test methods in Khwisero end of season 2

Treatment	Soil P pools (kg ha^{-1})							
P treat	RP-Pi		NaHCO$_3$-Pi		ExP		NaHCO$_3$-Po	
	Tithonia	Urea	Tithonia	Urea	Tithonia	Urea	Tithonia	Urea
Control	9.7	8.1	6.1	5.8	4.5	3.2	38	35
50 TSP	14	14	7.5	7.7	6.1	5.8	38	35
50 MPR	13	11	6.9	7.1	5.0	5.6	35	38
250 TSP	56	45	28	24	25	21	40	39
250 MPR	36	39	16	16	13	13	36	37
SED P	3.0		1.3		1.3		0.98	
SED N	2.1		0.96		0.95		0.69	
SED P x N	4.3		1.9		1.9		1.4	

SED = standard error of difference in means, ExP = Modified Olsen P, LSD =SED * T (at specified significance level)

Although not significantly different, RP-Pi from MPR + tithonia was higher than MPR + urea in the sandy clay loam site in season 1 (Table 8) and in the clay loam site in season 2 (Table 9). This may be attributable to a possibility of increased dissolution of MPR by organic acids from decomposing tithonia. Composting of agricultural wastes with PRs is known to increase solubility of PRs (Ikerra *et al.*, 1994). Availability of P from phosphate rock to plants has been enhanced when mixed with organic matter such as compost (Iyamuremye and Dick, 1996). Phosphate rock is likely to be solubilized by biological activity and production of organic acids during composting. Although tithonia gave generally higher extractable Pi fractions than urea, their differences were small and often varying.

Although the sequential and the non-sequential P extraction methods were expected to give similar results in extractable RP-Pi from the same P source, this was found not to be the case. The main reasons for the variations even where the same P source or site is under consideration are not clear. However it is suspected that random errors during P extraction in the laboratory and sub-sampling for analysis and also the difference in soil:resin ratio may be the main cause of this observed difference.

Extractable $NaHCO_3$-Pi from TSP-treated soils was significantly higher ($P \leq 0.01$) than that from MPR- treated soils at the two sites (Tables7-10). The sandy clay loam soils had higher net extractable $NaHCO_3$-Pi than the clay loam soils in both seasons and in the two sources of P (Figures 3 and 4). The reasons for the two observations have already been outlined above (section 4.1).

TSP-treated soil had higher net extractable bicarbonate-EDTA Pi (ExP) than MPR-treated soil at both sites and in the two seasons (Figures 3 and 4). The main reason for this is that the bicarbonate-EDTA method having been developed for water-soluble P sources may, therefore, have been less responsive to MPR. Bicarbonate related extracts are known to underestimate available P in PR treated soils (MacKay *et al.*, 1984). This could mean that bicarbonate-EDTA is not a good method for P analysis where PRs have been used. It is also possible that due to the slower rate of dissolution of MPR, there were less of its dissolution products loosely bound to the soil hence the lower levels extracted.

Although the bicarbonate and the bicarbonate-EDTA apply similar principles in P extraction, there were variations in extractable P by the two methods. Inorganic P extractable by the bicarbonate-EDTA (ExP) was lower than that extractable by the bicarbonate extract ($NaHCO_3$-Pi) (Olsen method). The longer duration (30 minutes) of shaking for the bicarbonate method as compared to 10 minutes for the bicarbonate-EDTA method could have resulted in the release of Pi that may have been either strongly held or blocked by the soil microaggregates. The difference in soil:solution ration may possibly be another cause for this observed difference. In fact comparison of data derived from the different modifications of the Olsen method may not be possible due to strong dependence of results on minor methodological differences.

While there was a net positive extractable $NaHCO_3$-Po in TSP-treated soils in the sandy clay loam in both seasons, $NaHCO_3$-Po from MPR-treated soils was lower than the control at the two sites during the experimental duration (Figures 3 and 4). Reasons for the observed differences are outlined above (section 4.1).

4.3 Relationship between soil P pools and maize yield

Coefficients of determination (r^2) between five soil P pools from the sequential P extraction scheme, four from the conventional P extraction methods and grain yield ranged from 1×10^{-6} to 0.77 and varied with site, P sources and N sources (Table 11 and 12).

Clearly relationships between maize yield and soil P test methods differ for soils and with different fertilizer sources. The variations between the different soil P pool tests and maize yield indicate that the different P tests responded differently to P treatments. A principal reason for these variations is that the two P sources leave different amounts and types of residues in the soil (Kumar *et al.*, 1993) and that different reagents for P extraction methods dissolve different amounts of P from the various P residues present in fertilized soils. These diverse P compounds (P reaction products) differ considerably in their solubility in the reagents that are used as soil tests for plant available P. The solubilities of these P reaction products in the P extraction reagents depend *inter alia* on the chemical composition of both compounds and reagents. Soil constituents (hydrous oxides of Al and Fe) mostly sorb soluble P fertilizers. Phosphate rocks do not easily dissolved and, therefore, remain as apatite in the soil (Menon and Chien, 1995). Because of the sparingly soluble nature of PRs, less of their reaction products may be in soil solution and, therefore, less of the same may be detected by the methods used in this study.

Table 11: Coefficients of determination (r^2) between sequentially extracted soil P pools and maize yield

Season	Site	P source		Soil P pools (kg ha^{-1})				
				RP-Pi	NaHCO$_3$-Pi	NaOH-Pi	NaHCO$_3$-Po	NaOH-Po
1	Nyabeda	TSP	U	0.74***	0.77***	0.70***	0.002	0.09
			T	0.53**	0.44*	0.40*	0.02	0.17
		MPR	U	0.49*	0.28	0.33*	0.03	0.11
			T	0.22	0.34	0.39*	0.03	0.03
	Khwisero	TSP	U	0.54**	0.62**	0.51**	0.007	0.30
			T	0.48*	0.45*	0.44*	0.03	0.04
		MPR	U	0.74***	0.70***	0.51**	0.008	0.13
			T	0.64**	0.67**	0.36*	0.000001	0.13
2	Nyabeda	TSP	U	0.70***	0.50**	0.60**	0.0002	0.34
			T	0.43*	0.39*	0.41*	0.0005	0.04
		MPR	U	0.53**	0.39*	0.51**	0.07	0.01
			T	0.13	0.13	0.30	0.02	0.001
	Khwisero	TSP	U	0.40*	0.43*	0.37*	0.009	0.38
			T	0.43*	0.44*	0.29	0.26	0.09
		MPR	U	0.58**	0.58**	0.49*	0.08	0.01
			T	0.24	0.30	0.069	0.28	0.0008

T = tithonia, U = urea, *, **, *** indicate significance at 0.05, 0.01 and 0.001 probability levels respectively

Table 12: Coefficients of determination (r^2) between non-sequential soil P pools and maize yield

Season	Site	P source		Soil P pools (kg ha^{-1})			
				RP-Pi	$NaHCO_3$-Pi	ExP	$NaHCO_3$-Po
1	Nyabeda	TSP	U	0.69***	0.66***	0.66**	0.08
			T	0.68***	0.59**	0.40*	0.49*
		MPR	U	0.57**	0.49*	0.40*	0.18
			T	0.52**	0.40*	0.38*	0.15
	Khwisero	TSP	U	0.72***	0.54**	0.54**	0.03
			T	0.48*	0.55**	0.61**	0.04
		MPR	U	0.69***	0.76***	0.74***	0.05
			T	0.63**	0.68***	0.80***	0.01
2	Nyabeda	TSP	U	0.58**	0.45*	0.46*	0.24
			T	0.39*	0.40*	0.06	0.018
		MPR	U	0.51**	0.28	0.38*	0.05
			T	0.11	0.17	0.05	0.04
	Khwisero	TSP	U	0.39*	0.40*	0.44*	0.01
			T	0.51**	0.50**	0.51**	0.06
		MPR	U	0.56**	0.53**	0.67**	0.004
			T	0.44*	0.48*	0.45*	0.09

T = tithonia, U= urea, *, **, *** indicate significance at 0.05, 0.01 and 0.001 probability levels respectively. ExP = Modified Olsen extractable P

Coefficients of determination (r^2) for TSP-treated soils were generally higher than those from MPR treated soils in most of the P extraction methods. This indicates that the P extraction methods gave a better estimate of plant-available P from TSP-treated soils than did from the MPR-treated soils. The differences between TSP and MPR are mainly attributed to the difference in the nature and quantities of the reaction products from the two sources of P. This may also be directly linked to the fact that some of the P extraction methods especially the bicarbonate related extracts were developed for water-soluble P sources and may, therefore, not be very appropriate where sparingly soluble P sources like phosphate rocks have been used. Conventional extracting solutions may not be suitable for evaluating bioavailability of P in soils fertilized with PR because these reagents react with the soil and extract not only the P that will be available for plant use but also part of the P from PRs which under natural conditions may not be readily available (Menon and Chien, 1995). The higher r^2

values in TSP-treated soils are in agreement with findings reported by researchers working with Nigerian soils (Enwezor *et al.*, 1977).

Urea-treated soils had generally higher r^2 values than tithonia treated soils. This observation is inconsistent with the observed increase in yield in tithonia-treated soils (appendices 12 and 13). The main reason being that the soil P fractions used in the regression may not be the true representation of the P status of the soil. This is because addition of the N sources (urea and tithonia) was done two weeks after soil sampling for the determination of the P fractions used in this study. However, the P status may not have changed much as only 5.6 kg P ha^{-1} was added from tithonia with none coming from urea. It is therefore possible that the P fractions from urea were possibly true representatives of the P status in the soil. Addition of 5.6 kg P ha^{-1} from tithonia may have slightly changed the P status of these soils.

The most labile Pi fractions (RP-Pi, $NaHCO_3$-Pi and ExP) were the three P fractions most strongly correlated to maize yield in TSP-treated soils (Tables 11 and 12). The above findings suggest that the three methods performed equally well in determining plant available P where soil was fertilized with TSP. This means that most of the dissolved fertilizer products from TSP were either in the soil solution or loosely bound to Fe components of the soil and were easily extractable by the plant. This confirms the findings of others that P extractable by these methods is readily plant available (Bowman *et al.*, 1978) and does reflect short term changes in plant available P (Hedley *et al.*, 1982).

The high coefficients of determination of RP-Pi, irrespective of soil type and P source, is an indication that P was applied in large amounts that led to satisfying much of the P sorption capacity of these soils with the excess being in soil solution. Anion exchange resin acts as a sink of P mobilized in soil solution and the P measured depends only on the concentration of P mobilized in soil solution and not on the P source or properties of the soil (Menon and Chien, 1995). Anion exchange resin method is generally thought to be a better P extraction method than other procedures as it has little chemical effect on the soil properties (Sibbesen, 1983). The strong correlation values of RP-Pi in both the non-sequential and sequential P extraction procedures at both sites in MPR treated soils indicates that MPR had dissolved and provided soil solution P. This may have corresponded to the dissolution of the more soluble portion of apatites (Smyth and Sanchez, 1982).

Significant correlation coefficients between maize yield and $NaHCO_3$-Pi, ExP from the non-sequential and $NaHCO_3$-Pi from the sequentially extracted P are attributed to the fact most of the P in these soils was loosely bound to soil components and was therefore available for plant growth. Phosphorus from TSP on being released goes mainly into Al and Fe components of the soil and it is, therefore, more available in the short term (Hughes and Gilkes, 1994). The extracting solutions in the non-sequential bicarbonate P react with and dissolve P from these soil components. These results are consistent with those of Menon *et al.* (1989) who found that the Olsen extractable P was significantly correlated to dry matter yield and P uptake by maize in soils treated with TSP and PR. The Olsen test has been found to give a good measure of P availability (Yost *et al.*, 1982). However the ability of this method to predict P in soils with highly differing fertilizer properties is somewhat limited (Fixen and Groven, 1990).

The non-sequential P extraction methods (Table 12) had on average higher r^2 values than the sequential P extraction method (Table 11). This means that the non-sequential P extraction methods were better in determining plant available P. This is directly related to the methodological differences of these extraction methods in measuring plant available P in the soil. While the non-sequential P extraction methods use mild reagents for extracting P, the sequential P extraction method uses procedures that may yield P fractions that are in readily not available to plants, hence the lower r^2 values.

Although NaOH-Pi showed strong coefficients of determination in especially in TSP-treated soils (Table 11), this does not indicate that this fraction was an important source of plant available P in these highly fertilized soils. NaOH-Pi is supposedly a Pi form strongly adsorbed to the surfaces of crystalline and non-crystalline Al and Fe oxides (Williams *et al.*, 1980). Sodium hydroxide inorganic P includes a slowly labile Pi pool that is an important source of available P within the time frame of 2-10 years (Beck and Sanchez, 1994). Studies on Ultisols fertilized with P for four years (Linguist *et al.*, 1997) and ten years (Schmidt *et al.*, 1996) found that NaOH-Pi fraction was a sink for fertilizer P applied in excess of plant uptake.

All the organic P fractions in the different methods of P extraction were poorly correlated to crop yield (Tables 11 and 12). The weaker correlations in the organic P fractions as compared to the inorganic P fractions is an indication that these fractions did not form important sources of plant available P in the two sites. This is because only a small fraction of the total soil Po is labile in the short term, the vast majority of the Po occurs in stabilized soil organic matter (SOM) and is not easily mineralized. These findings are consistent with those of Maroko *et al.* (1999) who observed that $NaHCO_3$-Po was not related to maize yield in western Kenya. This suggests that much of the $NaHCO_3$-Po was not readily mineralizable. NaOH-Po is thought to be involved in long term transformations in temperate soils (Batsula and Krivonosa, 1973) but undergoing seasonal transformations in tropical soils (Ball-Coelho *et al.*, 1993). It is thought to contain P associated with humic compounds and P sorbed on Fe and Al oxides (Cross and Schlesinger, 1995). NaOH-Po can be an important source of P for microorganisms especially where labile Pi is low (Chauhan *et al.*, 1981). It has recently been identified as an important source of plant available P in unfertilized tropical soil (Beck and Sanchez, 1994; Tiessen *et al.*, 1992; (Maroko *et al.*, 1999).

Significant coefficients of determination observed in season two especially in MPR-treated soil are probably a result of the continuing dissolution of this source of P overtime. This is confirmed by the higher relative agronomic effectiveness of MPR in season 2 (Table 13). Phosphate rocks are known to release P gradually into the soil solution with their residual effects becoming evident gradually (Khasawneh and Doll, 1978). In comparing residual effects, it must be remembered that with soluble fertilizers, the residual effect is derived from the soil-phosphate reaction products, mainly complexes of Ca, K, Fe, Al, and ammonium phosphates (Sample *et al.*, 1980). The reaction of prime importance is the conversion of P from labile to non-labile forms, while in PRs the PR-P needs to be released into solution before any residual effect can manifest itself. Therefore, in the short term, one is likely to find a poorer residual effect from PR application. The residual effects of PR relative to those of soluble P sources depend on, in addition to the rate of loss of P from the available P pool, the previous pattern of P application and the rate of dissolution of PR. The lower relative agronomic effectiveness (RAE) in season 1 at the two sites (Table 13) may be due to the small extent of dissolution of MPR on these soils and therefore less P being available for plant uptake. An increase in RAE in season 2 indicates more labile Pi in soil solution resulting from the gradual dissolution of MPR.

Table 13: Relative agronomic effectiveness of MPR at the two sites and seasons

Season	Site	RAE % in different treatment combination	
		urea	tithonia
1	Nyabeda	75	68
	Khwisero	120	108
2	Nyabeda	98	85
	Khwisero	106	79

The completely insignificant correlations between microbial biomass P (MBP) and C (MBC) and maize yield at the two sites (Table 14) indicate that these components did not form important plant available P in these highly fertilized soils.

Table 14: Coefficients of determination (r^2) between microbial biomass P and C and maize yield

Fertilizer combination	Microbial biomass fractions			
	Site			
	Nyabeda		Khwisero	
	MBP	MBC	MBP	MBC
TSP + tithonia	0.028	0.033	0.035	0.002
MPR + tithonia	0.036	0.173	0.018	0.003
TSP + urea	0.126	0.009	0.330	0.030
MPR + urea	0.560	0.029	0.003	0.048

This could be attributed to the fact that, labile Pi from inorganic P fertilization was in excess of plant uptake and therefore the significantly low P from the microbes may have had insignificant influence on maize yield. However in a separate study on similar sites without P fertilization, the above two components showed significant correlation with maize yield (Maroko *et al.*, 1999).

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

1. The sizes and changes in the labile P fractions were dependent on the rate of inorganic P fertilization. Phosphorus applied at 250 kg ha^{-1}year^{-1} as either TSP or MPR compared to 50 kg ha^{-1} year^{-1} and the control had significant effect on the inorganic P fractions over two seasons. TSP had higher extractable labile inorganic P fractions (RP-Pi, $NaHCO_3$-Pi and NaOH-Pi) than MPR.
2. The release and distribution of P into various fractions is dependent on the P source and soil characteristics. The clay loam soil had most of the Pi in the moderately labile (NaOH-Pi) form while the sandy clay loam site had more Pi in the readily labile (RP-Pi, $NaHCO_3$-Pi) fractions.
3. The organic P fractions ($NaHCO_3$-Po and NaOH-Po) were not influenced by the P source, P rate or N source.
4. Labile inorganic P fractions had stronger correlations to maize yield as compared to organic P fractions. This is attributable to the fact that inorganic P forms are more readily plant-available. TSP had generally higher coefficients of determination between maize yield and soil P than MPR on the two sites studied.
5. The higher relative agronomic effectiveness (RAE) observed at Khwisero makes MPR a good P source at this site. There were however variations in the two seasons indicating the importance of time on the relationship between P availability from MPR and crop yield.
6. Traditional soil tests developed for evaluating P availability in soils fertilized with soluble P fertilizers may not work well in soils treated with sparingly soluble

fertilizers such as MPR because the performance of these P sources in the soil depends on such factors as reactivity of the PR, soil properties and climatic conditions

7. The non-sequential P test methods were better in testing for P availability than the sequential P extraction method. Anion exchange resin in the non-sequential P test was the most reliable method of testing for plant-available P by the two P sources and sites.
8. Considering effectiveness on the two P sources, correlation with anion exchange resin seems to be the best method for determining available P in acid soils in western Kenya on which either TSP or MPR has been applied.

5.2 RECOMMENDATIONS

1. Although the sequential P extraction method is able to extract both the labile and non-labile P fractions as a way of estimating plant available P, the non-sequential tests were found to be more reliable and are, therefore, recommended.
2. To fully appreciate the residual effects of MPR and to be able to monitor the fate of the various P fractions from the two sources of P, long-term experiments need to be established.
3. A much wider range of soil types should be investigated to determine the influence of soil properties on soil extraction methods, yield correlations with and without various P sources.
4. The relationship between the P rates, sources and the enzyme phosphophatase on P release patterns from the two P sources should be investigated.
5. Since it is impossible to conduct field studies on all soil series, laboratory and greenhouse studies should be done to determine which soils could be grouped

together because of similar chemical properties as regards P reactions and availability.

6. Application of TSP in highly weathered soils may not be advisable for short term crops as most of the P will quickly be converted to NaOH-Pi, a fraction that is not available in the short term.

REFERENCES

Adepetu, J.A., and Corey, R.B. (1976) Organic phosphorus as a predictor of plant available phosphorus in soils of southern Nigeria. *Soil Sci.* 122: 159-164.

Agbenin, J.O. and Goladi, J.T. (1997) Carbon, Nitrogen and Phosphorus dynamics under continous cultivation in the savanna as influenced by farmyard manure and inorganic fertilizer application. *Agriculture , Ecosystems and Environment* 63, 17-24.

Anderson, D.L., Kussow, W.R., and Corey, R.B. (1985) Phosphate rock dissolution in soil: Indications from plant growth studies. *Soil Sci. Soc. Am. J.* 49: 918-925.

Anderson, J.M., and Ingram, J.S.I. (1993) Tropical Soil Biology and Fertility. A handbook of methods, 2nd Edition. *CAB International,* Wallingford, UK.

Anon. (1982) Groupo de trabajo de normalisacion de metodos analiticos. Revision bibligrafica de metodos de extraction de phosphoro assimilable en Suelos 1957-1980. Pages 1085-1112. In: Anales de Edafologia y Agrobiologia 41.

Baanante, C.A. (1997) Economic evaluation of the use of phosphate fertilizers as a capital investment. In: A.E. Johnston and J.K. Syers (ed.) Nutrient management for sustainable food production in Asia. *CAB International,* Wallingford, UK.

Ball-Coelho, B., Salcedo, I.H., Tiessen, H., and Stewart, J.W.B. (1993) Short and long term phosphorus dynamics in a fertilized Ultisol under sugarcane. *Soil Sci. Soc. Am. J.* 57: 1027-1034.

Batiano, A., Baethgen, W.E., Christianson, C.B., and Mokwunye, A.U. (1991) Comparison of five soil testing methods to establish phosphorus sufficiency levels in soil fertilized with water soluble and sparingly soluble-P sources. *Fert. Res.* 28: 271-279.

Batsula, A.A., and Krivonosova, G.M. (1973) Phosphorus in humic and fulvic acids of some Ukrainian soils. *Sov. Soil. Sci.* 5: 347-350.

Beck, A.M., and Sanchez, P.A. (1994) Phosphorus fraction dynamics during 18 years of cultivation on a Typic Paleudult. *Soil Sci. Soc. Am. J.* 58: 1424-1431.

Beck, M.A. (1991) Inorganic and organic phosphorus transformations during 18 years of cultivation in the Amazon Basin. M.Sc. Thesis. North Carolina State University. Raleigh.

Bekele, T., and Höfner, W. (1993) Effects of different phosphate fertilizers on yield of barley and rape seed in reddish soils of Ethiopian Highlands. *Fert. Res.* 34: 243-250.

Bolan, N.S., and Hedley, M.J. (1990) Dissolution of phosphate rocks in soils. II. Effects of pH on the dissolution and plant availability of phosphate rock in soil with pH dependent charge. *Fert. Res.* 24: 125-134.

Bolland, M.D.A., and Gilkes, R.J. (1990) Rock phophates are not effective fertilizers in Western Australian soils: a review of one hundred years of research. *Fert. Res.* 22: 79-95.

Bowman, R.A., and Olsen, S.R. (1979) A reevaluation of phosphorus-32 and resin methods in a calcareous soil. *Soil Sci. Soc. Am. J.* 43: 121-124.

Bowman, R.A., Olsen, S.R., and Watanabe, F.S. (1978) Greenhouse evaluation of residual phosphate by four phopsphorus methods in neutral and calcareous soils. *Soil Sci. Soc. Am. J.* 42: 451-454.

Brady, N.C., and Weil, R.R. (1996) The nature and properties of soils. 11th ed. Printice Hall, International Editions.

Bray, R.M., and Kurtz, L.T. (1945) Determination of total organic and available forms of phosphorus in soils. *Soil Sci.* 59: 39-45.

Brewster, J.L., Gancheva, A.N., and Nye, P.H. (1975) The determination of desorption isotherms for soil phosphate using low volumes of solution and an anion exchange resin. *J. Soil Sci.* 26: 364-377.

Brookes, P.C., Powlson, D.S., and Jenkinson, D.S. (1984) Phosphorus in soil microbial biomass. *Soil Biol. Biochem.* 16: 169-175.

Buresh, R.J., Smithson, P.C., and Hellums, D.T. (1997) Building soil P capital in sub-Saharan Africa. In: Buresh, R.J. and Sanchez, P.A. (eds). Replenishing Soil fertility in Africa. pp 111-149. SSSA Special Publication 51. SSSA and ASA, Madison, Wisconsin, USA.

Chang, S.C., and Jackson, M.L. (1957) Fractionation of soil phosphorus. *Soil Sci.* 84: 133-144.

Chauhan, B.S., Stewart, J.W.B., and Paul, E.A. (1981) Effect of labile inorganic phosphate status and organic carbon additions on the microbial uptake of phosphorus in soils. *Can. J. Soil Sci.* 61: 373-385.

Chien, S.H. (1978) Interpretation of Bray 1 extractable phosphorus from acid soil treated with phosphate rocks. *Soil Sci.* 126: 371-375.

Chien, S.H., Sale, P.W.G. and Hammond, L.L. (1990) Comparison of effectiveness of phosphorus fertilizer products. In: "Phosphorus requirements for sustainable agriculture in Asia and Oceania". International Rice Research Institute, Manila, Philippines. Pp.143-156.

Condron, L.M. and Goh, K.M. (1989) Effects of phosphatic fertilizers applications on amounts and forms of phosphorus in soils under irrigated pasture in New Zealand. *J. Soil Sci.* 40: 383-395.

Cook, P.J., Banerjee, D.M., and Southgate, P.N. (1990) The phosphorus resources of asia and Oceania. In: Phosphorus requirements for a sustainable agriculture in Asia and Oceania. International Rice Research Institute, Manila, Philippines, pp. 97-114.

Cosgrove, D.J. (1977) Microbial transformations in the phosphorus cycle. In: Advances in Microbial Ecology (M. Alexander, ed.) Vol 1, pp 95-135. Plenum Press, New York.

Cross, A.F., and Schlesinger, W.H. (1995) A literature review and evaluation of the Hedley fractionation: Applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. *Geoderma* 64: 197-214.

Dalal, R.C., and Hallsworth, E.G. (1976) Evaluation of parameters of soil phosphorus availability factors in predicting yield response and phosphorus uptake. *Soil Sci. Soc. Am. J.* 40: 541-546.

Deckers, J. (1993) Soil fertility and environmental problems in different ecological zones of the developing countries of sub-Saharan Africa. In: van Reuler, H. and Prins, W.H. (ed.) The role of plant nutrients and sustainable food production in sub-Saharan Africa. Ponsen & Looijen, Wageningen, The Netherlands. P.37-52.

Enwezor, W.O. (1977) Soil test for phosphorus in some Nigerian soils. 1. Comparison of methods of determining available phosphorus in soils of south eastern Nigeria. *Soil Sci.* 123: 48-53.

Fixen, P.E., and Grove, J.H. (1990) Testing soil for phosphorus. In: Westerman, R.L. (ed.) 3rd ed. Soil Testing and Plant Analysis. Soil Sci. Soc. Am, Madison, WI. pp 141-180.

Fox, R.L., and Kamprath, E.J. (1970) Phosphate sorption isotherms for evaluating the phosphate requirements of soil. *Soil Sci. Soc. Am. Proc.* 34: 902-907.

Frossard, E., Stewart, J.W.B., and St. Arnaud, R.S. (1989) Distribution and mobility of phosphorus in grassland and forest soils of Saskatchewan. *Can. J. Soil Sci.* 69: 40-416.

Frossard, E.M., Hedley, M.J. and Metherell, A. (1995) Reactions controlling the cycling of P in soils. In: Tiessen, H (ed.) Phosphorus in the global environment. John Wiley and sons Ltd., New York, p. 107-137.

Gahoonia, T.S., and Nielsen, N.E. (1992) The effect of root induced pH changes on the depletion of inorganic and organic phosphorus in the rhizosphere. *Plant Soil* 143: 185-191.

Gijsman, A.J., Oberson, A., Tiessen, H., and Friesen, K.D. (1996) Limited applicability of the CENTURY model in highly weathered Tropical soils.

Gunary, D., and Sutton, C.D. (1967) Soil factors affecting plant uptake of phosphate. *J. Soil Sci.* 18: 167-173.

Hammond, L.L. and Leon, L.A. (1983) Agronomic effectiveness of natural and altered phosphate rocks from Latin America. In: Proc. Int. Congr. On phosphorus compounds. World phosphorus Inst., Brussels, Belgium, p. 503-518.

Hammond, L.L., Chien, S.H., and Easterwood, G.W. (1986) Agronomic effectiveness of Bayovar phosphate rock in soil with induced phosphorus retention. *Soil Sci. Soc. Am .J.* 50: 1601-1606.

Haynes, R.J. (1992) Relative ability of a range of crop species to use phosphate rock as a P source when grown in soil. *J. Sci. Food Agric.* 74: 1-7.

Hedley, M.J., Stewart, J.W.B. and Chauhan, B.S. (1982) Changes in inorganic and organic phosphorus fractions induced by cultivation and by laboratory incubations. *Soil Sci. Soc. Am. J.* 46: 970-976.

Hellums, D.T., Baanante, C.A., and Chien, S.H. (1992) Alternative phosphorus fertilizers for the tropics: an agronomic and economic evaluation. In: Proceedings of the tropsoils phosphorus decision support system workshop, College Station, TX, 11-12 March 1992. pp. 147-154.

Hughes, J., and Gilkes, R.J. (1994) Rock phosphate dissolution and bicarbonate solution P in some soils from south western Australia. *Aust. J. Soil Res.* 32: 767-779.

Ikerra, T.W.D., Mnkeni, P.N.S., and Singh, B.R. (1994) Effects of added compost and farm yard manure on P release from Minjingu phosphate rock and its uptake by maize. *Norwegian Journal of Agricultural Sciences.* 8: 13- 23.

Iyamuremye, F., and R.P. Dick (1996) Organic ammendments and phosphorus sorption by soils. *Adv. Agron.* 56: 139-185.

Jackson, M.L. (1958) Soil Chemical Analysis. Pretince-Hall. Eaglewood Cliffs, NJ.

Jama, B., Swinkels, R.A., and Buresh, R.J. (1997) Agronomic and economic evaluation of organic and inorganic sources of phosphorus in western Kenya. *Agron. J.* 89: 597-604.

Jenkinson, D.S., and Ladd, J.N. (1981) Microbial biomass in soil: measurements and turnover . In: Paul, E.A. and Ladd, J.N. (eds.) Soil biochemistry, Vol. 5, Marcel Dekker, New York. pp 415-471

Kamprath, E.J., and Waston, M.E. (1980) Conventional soil and tissue test for assesssing the phosphorus status of soils. In: Khasawneh et al. (eds.) The role of phosphorus in agriculture. ASA, Madison, Winconsin. pp. 433-489.

Kanabo, I., and Gilkes, R.J. (1988) The effects of moisture regime and incubation period on the dissolution of North Carolina phosphate rock in soil. *Aust. J. Soil. Res.* 26: 153-163.

Kanabo, I.A.K., and Gilkes, R.J. (1987) The role of soil pH on the dissolution of phosphate rock fertilizers. *Fert. Res.* 12: 165-174.

Khasawneh, F.E., and Doll, E.C. (1978) The use of phosphate rock for direct application to soils. *Adv. Agron.* 30: 159-205.

Kumar, V., Gilkes, R.J., and Bolland, M.D.A. (1993) Forms of phosphate in soil fertilized with rock phosphate and superphosphate as measured by chemical fractionation. *Aust. J. Soil Res.* 31: 465-480.

Kuono, K., Tuchiya, Y., and Ando, T. (1995) Measurement of microbial biomass phosphorus by an anion exchange membrane method. *Soil Biol. Biochem.* 27: 1353-1357.

Lane, P., Galwey, N. and Alvey, N. (1987) Genstat 5. An Introduction, pp 44-65. Oxford Science Publications, Oxford, England; Clarendon Press, New York.

Lin, T.H., Ho, S.B., and Houng, K.H. (1991) The use of iron oxide impregnated filter paper for the extraction of available phosphorus from Taiwan soils. *Plant Soil* 133: 219-226.

Lindsay, W.L., and Moreno, E.C. (1960) Phosphate phase equilibrium in soils. *Soil Sci Soc. Am. Proc.* 24: 177-187.

Linquist, B.A., Singleton, P.W., and Cassman, K.G. (1997) Inorganic and organic phosphorus during dynamics during a build-up and decline of available phosphorus in an Ultisol. *Soil Sci. 162:254-264.*

Mackay, A.D., Syers, J.K., Gregg, P.E.H. and Tillman, R.W. (1984) A comparison of three soil testing procedures for estimating the plant available phosphorus in soil receiving either superphosphate or phosphate rock. New Zealand *J agric. Res.* 27: 231-245.

Marks, G. 1977. Beitrag zur prazisierten charakterisierung von Pflanzen-verfugbarem phosphat in Ackerboden. Arch. Acker pflanzenbau Bodenkd. 21: 447-456.

Maroko, J., Buresh, R.J. and Smithson, P.C. (1999) Soil phosphorus fractions in unfertilized fallow-maize systems on two tropical soils. *Soil Sci. Soc. Am. J.* (in press)

Mattingly, G.E.G. (1975) Labile phosphate in the soil. *Soil Science*119: 369-375.

McLaughlin, J. R., Ryden, J.C., and Syers J.K. (1977) Development and evaluation of a kinetic model to describe phosphate sorption by hydrous ferric oxide gel. Geoderma 18: 295-307.

Menon, R.G., and Chien, S.H., (1995) Soil testing for available phosphorus in soils where phosphate rock-based fertilizers are used. *Fertilizer Research* 41: 179-187.

Menon, R.G., Chien, S.H., and Hammond, L.L. (1989) Comparison of Bray 1 and Pi tests for evaluating plant-available phosphorus from soils treated with different partially acidulated phosphate rocks. *Plant Soil* 114: 211-216.

Moser, U.S., Sutherland, W.H., and Black, C.A. (1959) Evaluation of laboratory indexes of absorption of soil phosphorus by plants: 1. *Plant Soil* 10: 356-374.

Moshi, A.O., Wild, A., and Greenland D.J. (1974) Effect of organic matter on the charge and phosphate adsorption characteristics of Kikuyu red clay from Kenya. *Geoderma* 11: 275-285.

Murphy, J., and Riley, J.P. (1962) A modified single solution for the determination of phosphorus in natural waters. *Analy Chimica Acta* 27: 31-36.

Murwira, K.H., Swift, M.J., and Frost, P.G.H. (1995) Manure as a key resource in sustaininable agriculture. In: Powell, L.M. Fernandez - Rivera, S., Williams, O.T., and Renard, C. (ed). Livestock and sustainable nutrient cycling in mixed farming systems of sub-saharan Africa. Vol. II: Technical papers. Proceedings of conference, International Livestock Centre for Africa, Addis Ababa, Ethiopia. pp 131 - 148

Mutuo, P.K., Smithson, P.C., Buresh, R.J., and Okalebo, R.J. (1999) Comparison of phosphate rock and triple superphosphate on a phosphorus deficient Kenyan soil. *Commun. Soil Sci. Plant Analy.* (in press)

Nelson, D.W., and Sommers, L.E. (1982) Total carbon, organic carbon and organic matter. In: Page, A.L., Miller, R.H., and Kearney, D.R (eds), Methods of soil analysis. Part 2. Chemical and microbiological properties American Society of Agronomy, Madison, Winconsin, pp. 539-580.

Nelson, W.L., Mehlich, A., and Winters, E. (1953) The development, evaluation and use of soil tests for phosphorus availability. *Agronomy* 4: 153-158.

Nurwakera, J. (1991). Soil phosphorus dynamics during continuous cultivation in Brazilian Amazon Oxisol. MSc. Thesis, North Carolina State University, Raleigh, pp.1-117.

Nziguheba, G., Palm, C.A., Buresh, R.J., and Smithson, P.C. (1998) Soil phosphorus fractions and adsorption as affected by organic and inorganic sources. *Plant Soil* 198: 159-168.

O'Halloran, I.P., Stewart, J.W.B., and Kachonoski, R.G. (1987) Influence of texture and management practices on soil forms and distribution of soil phosphorus. *Can. J. Soil Sci.* 67: 147-163.

Olsen, S.R., and Sommers L.E. (1982) Phosphorus. Pp 403-430. In: Page, A.L., Miller, R.H., and Kearney, D.R (eds) Methods of Soil Analysis 2nd Ed Part 2 (Am Soc Agron.) Madison, USA.

Olsen, S.R., Cole, C.V., Watanabe, F.S., and Dean, L.A. (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. US Department of Agriculture Circular 930. US Government Printing Office. Washington DC, USA.

Palm, C.A. (1995) Contribution of agroforestry trees to nutrient requirements of intercropped plants. *Agroforestry Systems* 30: 105-124.

Patel, B.N. (1975) Minjingu phosphate rock- a raw fertilizer material of local origin. Paper presented at the 1st meeting of the Soil Science Society of East Africa.

Peterson, G.W., and Corey, R.B. (1966) A modified Chang and Jackson procedure for routine fractionation of inorganic soil phosphorus. *Soil Sci. Soc. Am. Proc.* 30: 563-565.

Rajan, S.S.S., Fox, R.I., Saunders, W.M.H., and Upsdell, M.P. (1991) Influence of pH, time and rate of application on phosphate rock dissolution and availability on pastures. I. Agronomic benefits. *Fert. Res.* 28: 85-93.

Rajan, S.S.S., Watkinson, J.H., and Sinclair, A.G. (1996) Phosphate rocks for direct application to soils. *Adv. Agron.* 57: 77-159.

Reinertsen, S.A., Elliott, L.F., Cochran, V.L., and Campell, G.S. (1984) Role of available carbon and nitrogen in determining the rate of straw decomposition. *Soil Biol. Biochem.* 16: 459-464.

Robinson, J.S., Syers, J.K., and Bolan, N.S. (1992a) influence of calicium carbonate on dissolution of Sechura phosphate rock in soils. *Fert. Res.* 32: 91-99.

Ryden, J.C., McLaughlin, J. R., and Syers J.K. (1977) Time-dependent sorption of phosphate by soils and hydrous ferric oxides. *J. Soil Sci.* 28: 585-595.

Saggar, S., Hedley, M.J., and White, R.E. (1992a) Development and evaluation of an improved soil test for phosphorus: 1. The influence of phosphorus fertilizer solubility and soil properties on the extrability of soil P. *Fert. Res.* 33: 81-91.

Sample, E.C., Soper, R.J. and Racz, G.J. (1980) Reactions of phosphate fertilizers in the soil. In: F.E. Khasawneh, F.E., Sample, E.C., and Kamprath, E.J. (eds). *The Role of phosphorus in agriculture.* Agron, Crop sci. Madison, WI.

Sanchez, P.A. (1976) Properties and management of soil in tropics. John Wiley and sons, New York.

Sanchez, P.A. 1980. Role of phosphorus in Agriculture (1982) In: F.E. Khasawneh, F.E., Sample, E.C., and Kamprath, E.J. (eds). Agron, Crop sci. Madison, WI.

Sanchez, P.A., and Uehara. G. (1980) Management constraints for acid soils with high phosphorus fixation capacity. In: F.E. Khasawneh, F.E., Sample, E.C., and Kamprath, E.J. (eds). The role of phosphorus in agriculture. Soil Science Society of America. Madson, Wisconsin. Pp. 471-514.

Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A.M.N., Mokwunye, A.U., Kwesiga, F.R., Nderitu, C.G., and Woomer, P.L. (1997) Soil fertility replenishment in Africa: An investment in natural resource capital. In: Buresh, J.R. and Sanchez P.A. (eds). Replenishing soil fertility in Africa. Soil Science Society of America Special Pub. 51. SSSA and ASA, Madison, Wisconsin.p.1-46.

Sawhney, B.L. (1973) Electron microprobe analysis of phosphates in soils and sediments. *Soil Sci. Soc. Am. Proc.* 37: 658-660.

Schlesinger, W.H., Delucia, E., and Billings, W.D. (1989) Nutrient use efficiency of woody plants on contrasting soils in western Great Basin,. Nevada. *Ecology* 70: 105-113.

Schmidt, J.P., Buol, S.W., and Kamprath, E.J. (1996) Soil phosphorus dynamics during seventeen years of continuous cultivation: Fractionation analyses. *Soil Sci. Soc. Am J.* 60: 1168-1172.

Schnitzer, M. (1991) Soil organic matter-the next 75 years. *Soil Sci.* 151: 41-58.

Sharpley, A.N., Sims, J.T., and Pierzynski, G.M. (1994) Innovative soil phosphorus availability indices: assessing inorganic phosphorus. In: Harvin, J.L. and Jacobsen J.S. (eds.). Soil testing: prospects for improving nutrient recommendations. SSSA Spec. Pub. No. 40. *Soil Sci. Soc. Am.*, Madison, WI, pp 115-142.

Sharpley, A.N., Tiessen, H., and Cole, C.V. (1987) Soil phosphorus forms extracted by soil tests as a function of pedogenesis. *Soil Sci. Soc. A.m. J.* 51: 362-365.

Shepherd, K.D., Ohlsson, E., Okalebo, J.R., Ndufa, J.K. and David, S. (1995) A static model of nutrient flow on mixed farms in the highlands of western Kenya to explore the possible impact of improved management. In: Livestock Sustainable Nutrient Cycling in Mixed farming Systems of sub- Saharan Africa. Volume II. Technical Paper. Conf. Proceedings. Ethiopia.

Sibbesen, E. (1978) An investigation of the anion exchangeable resin method for soil phosphate extraction. *Plant and Soil* 50: 305-321

Sibbesen, E. (1983) Phosphate soil tests and their suitability to assess the phosphate status of soil. *J. Sci. Food Agric.* 34: 1368-1374

Smaling, E.M.A., Stoorvogel, J.J., and Windmeijer, P.N. (1993) Calculating soil nutrient balance in Africa at different scales. II District-scale. *Fert. Res.* 35: 237–250.

Smith, J.L., Papendick, R.I., Bezdicek, D.F., and Lynch, J.M. (1993) Soil organic matter dynamics and crop residue management. In: Blaine, M.F. Jr (ed.) Soil microbial ecology: Applications in agricultural and environment management. Marcel Decker, New York. PP 65-94.

Smyth, T.J., and Sanchez, P.A. (1982) Phosphate rock dissolution and availability in Cerrado soils as affected by phosphorus sorption capacity. *Soil Sci. Soc. Am. J.* 46: 339-346.

Sollins, P., Robertson, G.P., and Uehara, G. (1988) Nutrient mobility in variable and permanent charge soils. *Biogeochemistry* 6: 181-199.

Stevenson, F.J. (1986) Cycles of soil: carbon, nitrogen, phosphorus, sulfur, micronutrients. John Wiley and Sons, New York.

Stewart, J.W.B. and H. Tiessen. (1987) Dynamics of soil organic phosphorus. *Biogeochemistry* 4: 41-60.

Swift, M.J., Bohren, I., Carter, S.E., Izac, A.M.N, and Woomer, P.L. (1994) Intergrating process research and farm practice. In: Woomer, P.L. and Swift, M.J. (eds). Biological management of tropical soils. Wiley Sayce, Chichester, UK, pp 209-227.

Syers, J.K., and Mackay, A.D. (1986) Reaction of Sechura phosphate rock and single superphosphate in soil. *Soil Sci. Soc. Am. J.* 50: 480-485.

Szott, L.T., and Kass, D.S.L. (1993) Fertilizer in agroforestry. *Agroforestry Systems* 23: 157-176

Tiessen, H., and Moir, J.O. (1993) Characterization of available P by sequential extraction. In: Carter, M.R. (ed) Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, FL, pp. 75-86

Tiessen, H., Salcedo, I.H., and Sampaio, E.V.S.B. (1992) Nutrient and soil organic matter dynamics under shifting cultivation in semi-arid northeastern Brazil. *Agric. Ecosyst. Environ.* 38: 139-151.

Tiessen, H., Stewart, J.W.B., and Cole, C.V. (1984) Pathway of phosphorus transformations in soils of differing pedogenesis. *Soil Sci. Soc. Am. J.* 48: 853-858.

Tiessen, H., Stewart, J.W.B., and Moir, J.O. (1983) Changes in organic and inorganic phosphorus composition of two grassland soils and their particle size fractions during 60-90 years of cultivation. *J. Soil Sci.* 34: 815-823.

Tisdale, S.L., Nelson, W.L., and Beaton, J.D. (1985) Soil fertility and fertilizers. 4th edition. Macmillan Publ. Co., New York.

Trasar-Cepeda, M.C., Gil-Sotres, F., and Guitian-Ojea, F. (1987) Characterization of phosphorus in soils of Galicia: comparison of the methods of Chang and Jackson (1957), and Hedley et al. (1982). *Anales de Edafologia y Agrobiologia.* 46: 1361-1373.

Van Kauwenberg, S.J. (1991) Overview of phosphate deposists in eastern and southeastern Africa. *Fert. Res.* 30: 127-150.

Weil, S., Gregg, P.E.H., and Bolan, N.S. (1994) Influence of soil moisture on the dissolution of reactive phosphate rocks. In: Currie, L.D. and Loganathan, P. (eds) The Efficient Use of Fertilizers in a Changing environment: Reconciling productivity and Sustainability. Occasional Report No.7, Fertilizer and Lime Research Centre, Massey University, Palmerston North. pp 75-81.

Williams, J.D.H., Mayer, T., and Nriagu, J.O. (1980) Extractability of phosphorus from phosphate minerals common in soils and sediments. *Soil Sci. Soc. Am. J.* 44: 462-465.

Williams, J.D.H., Syers, J.K., and Walker, T.W. (1967) Fractionation of soil inorganic phosphorus by a modification of Chang and Jackson's procedure. *Soil Sci. Soc. Am. Proc.* 31: 736-739.

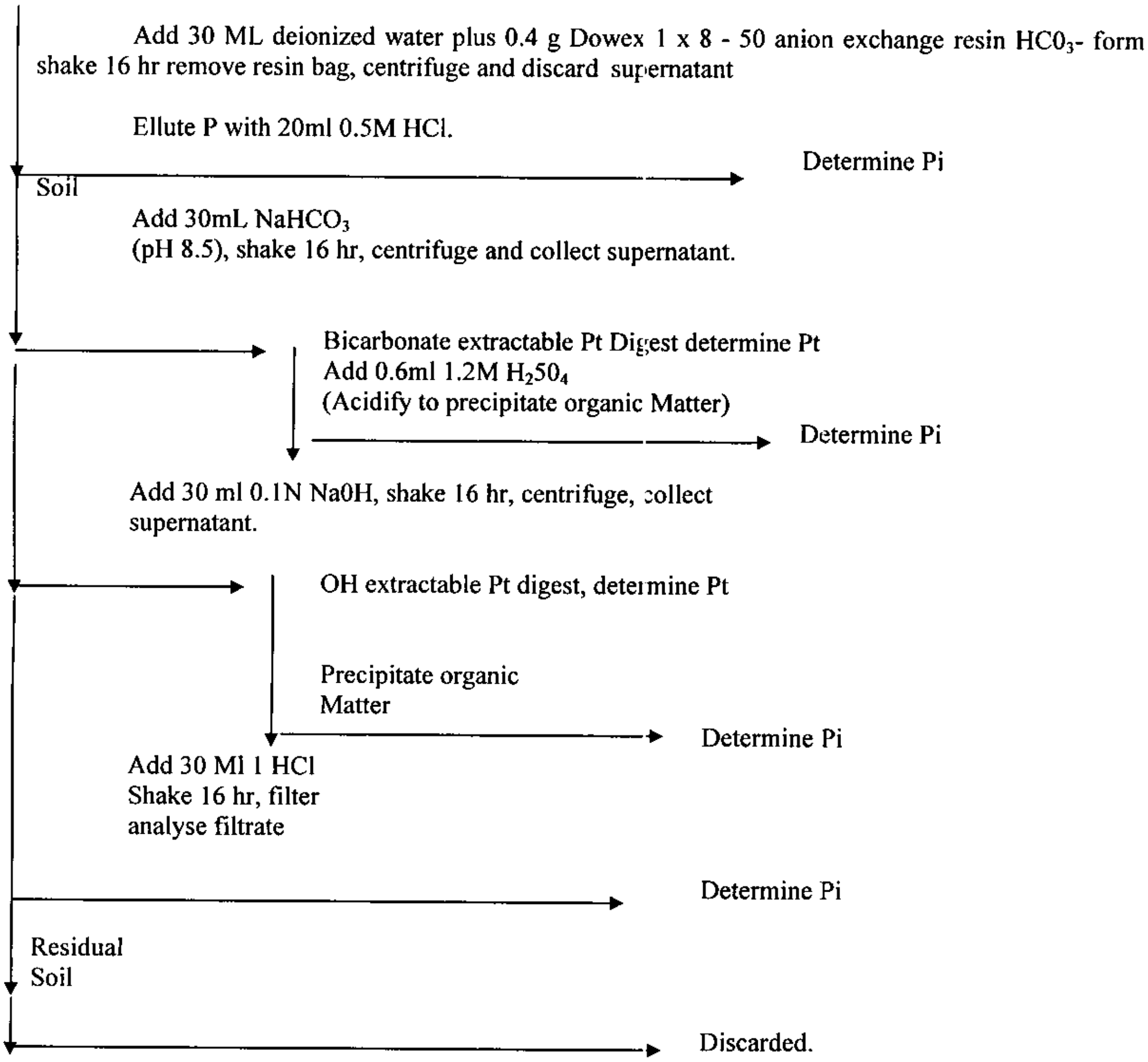
Williams, K.D.H., Syers, J.K. Harris, R.F., and Armstrong, D.E. (1971) Fractionation of inorganic phosphate in calcareous lake sediments. *Soil Soc. Am. Proc.* 35: 250-255.

Yost, R.S., Naderman, G.C., Kamprath, E.J., and Lobato, E. (1982) Availability of rock phosphate as measured by an acid tolerant pasture grass and extractable phosphorus. *Agron. J.* 74: 462-468.

APPENDICES

Appendix 1: Modified version of Hedley sequential phosphorus fractionation method for soils.

0.5g soil samples in 50 ml screw cap centrifuge tubes.



Add 30 ML deionized water plus 0.4 g Dowex 1 x 8 - 50 anion exchange resin $HC0_3$- form shake 16 hr remove resin bag, centrifuge and discard supernatant

Ellute P with 20ml 0.5M HCl.

Determine Pi

Soil

Add 30mL $NaHCO_3$
(pH 8.5), shake 16 hr, centrifuge and collect supernatant.

Bicarbonate extractable Pt Digest determine Pt
Add 0.6ml 1.2M H_250_4
(Acidify to precipitate organic Matter)

Determine Pi

Add 30 ml 0.1N Na0H, shake 16 hr, centrifuge, collect supernatant.

OH extractable Pt digest, determine Pt

Precipitate organic
Matter

Determine Pi

Add 30 Ml 1 HCl
Shake 16 hr, filter
analyse filtrate

Determine Pi

Residual
Soil

Discarded.

Appendix 2: Probability levels of the effect of treatments on sequentially extractable soil P pools Nyabeda end of season 1

Source of variation	d.f.	F pr					
		RP-Pi	$NaHCO_3$-Pi	NaOH-Pi	HCl-Pi	$NaHCO_3$-Po	NaOH-Po
Stratum	3						
Ptreat	1	<0.001	0.001	<0.001	<0.001	0.458	0.564
Nsource	1	0.951	0.309	0.521	0.706	0.880	0.214
Ptreat.Nsource	1	0.963	0.018	0.286	0.022	0.766	0.132

Appendix 3: Probability levels of the effect of treatments on sequentially extractable soil P pools Khwisero end of season 1

Source of variation	d.f.	F pr					
		RP-Pi	$NaHCO_3$-Pi	NaOH-Pi	HCl-Pi	$NaHCO_3$-Po	NaOH-Po
Stratum	3						
Ptreat	1	<0.001	<0.001	<0.001	<0.001	0.079	0.154
Nsource	1	0.130	0.430	0.353	0.437	0.551	0.825
Ptreat.Nsource	1	0.569	0.543	0.354	0.981	0.362	0.985

Appendix 4: Probability levels of the effect of treatments on sequentially extractable soil P pools Nyabeda end of season 2

Source of variation	d.f.	F pr					
		RP-Pi	$NaHCO_3$-Pi	NaOH-Pi	HCl-Pi	$NaHCO_3$-Po	NaOH-Po
Stratum	3						
Ptreat	1	<0.001	<0.001	<0.001	0.122	0.361	0.222
Nsource	1	0.020	0.328	0.185	0.587	0.673	0.833
Ptreat.Nsource	1	0.066	0.764	0.302	0.583	0.549	0.895

Appendix 5: Probability levels of the effect of treatments on sequentially extractable soil P pools Khwisero end of season 2

Source of variation	d.f.	F pr					
		RP-Pi	$NaHCO_3$-Pi	NaOH-Pi	HCl-Pi	$NaHCO_3$-Po	NaOH-Po
Stratum	3						
Ptreat	1	<0.001	<0.001	<0.001	<0.001	0.063	0.466
Nsource	1	0.215	0.049	0.108	0.020	0.678	0.792
Ptreat.Nsource	1	0.363	0.441	0.979	0.697	0.866	0.951

Appendix 6: Probability levels of the effect of treatments on Non-sequential soil P pools Nyabeda end of season 1

Source of variation	d.f.	F pr			
		RP-Pi	$NaHCO_3$-Pi	ExP	$NaHCO_3$-Po
Stratum	3				
Ptreat	3	<0.001	<0.001	<0.001	0.837
Nsource	1	0.63	0.718	0.067	0.359
Ptreat.Nsource	3	0.66	0.488	0.001	0.698

Appendix 7: Probability levels of the effect of treatments on Non-sequential soil P pools Khwisero end of season 1

Source of variation	d.f.	F pr			
		RP-Pi	$NaHCO_3$-Pi	ExP	$NaHCO_3$-Po
Stratum	3				
Ptreat	3	<0.001	<0.001	<0.001	0.520
Nsource	1	0.285	0.891	0.594	0.549
Ptreat.Nsource	3	0.750	0.569	0.831	0.605

Appendix 8: Probability levels of the effect of treatments on Non-sequential soil P pools Nyabeda end of season 2

Source of variation	d.f.	F pr			
		RP-Pi	$NaHCO_3$-Pi	ExP	$NaHCO_3$-Po
Stratum	3				
Ptreat	3	<0.001	<0.001	<0.001	0.228
Nsource	1	0.311	0.036	0.558	0.266
Ptreat.Nsource	3	0.664	0.163	0.050	0.792

Appendix 9: Probability levels of the effect of treatments on Non-sequential soil P pools Khwisero end of season 2

Source of variation	d.f.	F pr			
		RP-Pi	$NaHCO_3$-Pi	ExP	$NaHCO_3$-Po
Stratum	3				
Ptreat	3	<0.001	<0.001	<0.001	0.014
Nsource	1	0.227	0.473	0.300	0.842
Ptreat.Nsource	3	0.133	0.313	0.321	0.048

Appendix 10: % P recovered at the end of each season by sequential extraction method

Season	Site	P source	% P recovery of inorganic soil P pools				Total % P recovered
			RP-Pi	$NaHCO_3$-Pi	NaOH-Pi	HCl-Pi	
1	Nyabeda	TSP	8.4	6.0	22.4	0.4	37.2
		MPR	8.8	2.4	9.2	0.4	20.8
	Khwisero	TSP	16.8	7.6	21.2	0.8	46.4
		MPR	13.2	3.2	13.2	4.4	34
2	Nyabeda	TSP	7.2	5.2	24.4	0	36.8
		MPR	12.4	3.6	17.6	0	33.6
	Khwisero	TSP	15.6	8.8	30.8	1.2	56.4
		MPR	12.8	4.4	21.6	4.4	43.2

Appendix 11: % P recovered at the end of each season by non-sequential extraction methods

Season	Site	P source	% P recovery of inorganic soil P pools		
			RP-Pi	$NaHCO_3$-Pi	ExP
1	Nyabeda	TSP	10	6.4	3.2
		MPR	13	1.6	1.0
	Khwisero	TSP	13	6.4	5.0
		MPR	12	2.0	1.2
2	Nyabeda	TSP	6.4	5.2	2.0
		MPR	11	2.0	1.6
	Khwisero	TSP	17	8.0	7.5
		MPR	11	4.0	3.0

Appendix 12: Maize yield from respective treatments at Nyabeda (clay loam)

Treat No	Rep No	P Source	P rate	N rate	N source	K rate	K source	Season 1 Grain yield (T/Ha)	Season 2 Grain yield (T/Ha)	Season 3 Grain yield (T/Ha)
2	1	TSP	50	60	Urea	56	KCL	3.01	2.03	4.70
2	2	TSP	50	60	Urea	56	KCL	4.26	1.37	2.72
2	3	TSP	50	60	Urea	56	KCL	2.66	1.16	3.84
2	4	TSP	50	60	Urea	56	KCL	3.96	1.77	3.19
3	1	PR	50	60	Urea	56	KCL	3.78	2.48	4.81
3	2	PR	50	60	Urea	56	KCL	2.53	1.45	3.09
3	3	PR	50	60	Urea	56	KCL	3.64	1.51	3.26
3	4	PR	50	60	Urea	56	KCL	2.91	1.07	4.14
4	1	TSP	250	60	Urea	56	KCL	5.85	3.39	5.19
4	2	TSP	250	60	Urea	56	KCL	6.04	2.51	4.80
4	3	TSP	250	60	Urea	56	KCL	7.73	2.65	4.23
4	4	TSP	250	60	Urea	56	KCL	6.32	3.23	5.10
5	1	PR	250	60	Urea	56	KCL	3.70	2.79	4.75
5	2	PR	250	60	Urea	56	KCL	4.92	2.13	3.64
5	3	PR	250	60	Urea	56	KCL	3.50	1.28	5.88
5	4	PR	250	60	Urea	56	KCL	4.01	2.90	4.60
7	1	None	0	60	Tithonia	56	Tithonia	2.33	1.53	2.19
7	2	None	0	60	Tithonia	56	Tithonia	2.20	0.52	1.89
7	3	None	0	60	Tithonia	56	Tithonia	0.49	0.23	1.91
7	4	None	0	60	Tithonia	56	Tithonia	2.37	1.39	1.98
8	1	TSP	50	60	Tithonia	56	Tithonia	3.92	1.67	3.92
8	2	TSP	50	60	Tithonia	56	Tithonia	3.21	1.43	3.89
8	3	TSP	50	60	Tithonia	56	Tithonia	3.53	1.03	4.31
8	4	TSP	50	60	Tithonia	56	Tithonia	4.10	1.27	4.28
9	1	PR	50	60	Tithonia	56	Tithonia	2.71	1.61	4.27
9	2	PR	50	60	Tithonia	56	Tithonia	4.04	1.58	5.10
9	3	PR	50	60	Tithonia	56	Tithonia	2.55	1.75	4.96
9	4	PR	50	60	Tithonia	56	Tithonia	3.17	0.95	3.58
10	1	TSP	250	60	Tithonia	56	Tithonia	5.03	3.86	5.27
10	2	TSP	250	60	Tithonia	56	Tithonia	6.37	2.10	4.26
10	3	TSP	250	60	Tithonia	56	Tithonia	2.95	1.10	3.88
10	4	TSP	250	60	Tithonia	56	Tithonia	5.85	2.93	4.26
11	1	PR	250	60	Tithonia	56	Tithonia	4.09	2.10	3.88
11	2	PR	250	60	Tithonia	56	Tithonia	4.05	2.62	4.63
11	3	PR	250	60	Tithonia	56	Tithonia	3.78	1.95	3.98
11	4	PR	250	60	Tithonia	56	Tithonia	4.37	1.33	3.76
13	1	None	0	0	None	None	None	0.91	0.35	0.71
13	2	None	0	0	None	None	None	1.64	0.52	1.11
13	3	None	0	0	None	None	None	0.41	0.17	0.86
13	4	None	0	0	None	None	None	0.85	0.69	0.80
14	1	TSP	5.6	60	Urea	56	KCL	0.56	0.42	0.92
14	2	TSP	5.6	60	Urea	56	KCL	1.35	1.41	2.16
14	3	TSP	5.6	60	Urea	56	KCL	1.98	0.88	1.71
14	4	TSP	5.6	60	Urea	56	KCL	1.57	0.97	2.11

Maize grain yield expressed at 15.5% moisture content

Appendix 13: Maize yield from respective treatments at Khwisero (sandy clay loam)

Treat No	Rep No	P Source	P rate	N rate	N source	K rate	K source	Season 1 Grain yield (T/Ha)	Season 2 Grain yield (T/Ha)	Season 3 Grain yield (T/Ha)
2	1	TSP	50	60	Urea	56	KCL	4.54	1.02	4.43
2	2	TSP	50	60	Urea	56	KCL	2.72	0.64	5.08
2	3	TSP	50	60	Urea	56	KCL	3.85	1.04	5.12
2	4	TSP	50	60	Urea	56	KCL	4.11	1.06	5.24
3	1	PR	50	60	Urea	56	KCL	4.59	1.25	3.79
3	2	PR	50	60	Urea	56	KCL	3.34	0.73	6.09
3	3	PR	50	60	Urea	56	KCL	3.24	1.23	4.48
3	4	PR	50	60	Urea	56	KCL	3.77	1.22	3.92
4	1	TSP	250	60	Urea	56	KCL	5.49	2.46	5.63
4	2	TSP	250	60	Urea	56	KCL	2.19	1.88	4.78
4	3	TSP	250	60	Urea	56	KCL	5.76	0.95	6.08
4	4	TSP	250	60	Urea	56	KCL	6.59	1.55	6.66
5	1	PR	250	60	Urea	56	KCL	5.19	2.60	5.59
5	2	PR	250	60	Urea	56	KCL	5.42	1.67	6.30
5	3	PR	250	60	Urea	56	KCL	5.16	1.65	5.88
5	4	PR	250	60	Urea	56	KCL	5.59	2.17	6.36
7	1	None	0	60	Tithonia	56	Tithonia	3.20	0.82	2.98
7	2	None	0	60	Tithonia	56	Tithonia	3.58	0.71	4.00
7	3	None	0	60	Tithonia	56	Tithonia	1.84	0.17	2.58
7	4	None	0	60	Tithonia	56	Tithonia	2.02	0.26	3.22
8	1	TSP	50	60	Tithonia	56	Tithonia	5.36	1.55	6.27
8	2	TSP	50	60	Tithonia	56	Tithonia	3.17	1.68	5.59
8	3	TSP	50	60	Tithonia	56	Tithonia	4.42	1.24	6.82
8	4	TSP	50	60	Tithonia	56	Tithonia	4.41	1.87	4.71
9	1	PR	50	60	Tithonia	56	Tithonia	4.69	1.45	6.38
9	2	PR	50	60	Tithonia	56	Tithonia	2.62	1.42	3.11
9	3	PR	50	60	Tithonia	56	Tithonia	1.70	1.67	5.16
9	4	PR	50	60	Tithonia	56	Tithonia	3.76	1.36	4.52
10	1	TSP	250	60	Tithonia	56	Tithonia	6.23	2.07	7.79
10	2	TSP	250	60	Tithonia	56	Tithonia	6.08	2.28	6.62
10	3	TSP	250	60	Tithonia	56	Tithonia	6.28	2.43	6.49
10	4	TSP	250	60	Tithonia	56	Tithonia	5.90	3.27	6.78
11	1	PR	250	60	Tithonia	56	Tithonia	5.68	2.66	7.16
11	2	PR	250	60	Tithonia	56	Tithonia	3.74	2.96	4.27
11	3	PR	250	60	Tithonia	56	Tithonia	4.75	2.12	6.36
11	4	PR	250	60	Tithonia	56	Tithonia	5.69	2.88	6.69
13	1	None	0	0	None	None	None	1.68	0.04	0.73
13	2	None	0	0	None	None	None	1.27	0.00	0.78
13	3	None	0	0	None	None	None	0.90	0.00	1.05
13	4	None	0	0	None	None	None	0.65	0.00	0.80
14	1	TSP	5.6	60	Urea	56	KCL	1.84	0.38	1.88
14	2	TSP	5.6	60	Urea	56	KCL	2.02	0.22	2.37
14	3	TSP	5.6	60	Urea	56	KCL	1.93	0.18	2.63
14	4	TSP	5.6	60	Urea	56	KCL	1.30	0.00	1.85

Maize grain yield expressed at 15.5% moisture content