

**CHANGES IN SOIL PHOSPHORUS FRACTIONS IN RELATION TO  
PHOSPHORUS SOURCES AND THEIR INFLUENCE ON RESIDUAL  
PHOSPHORUS AVAILABILITY**

**BY**

**EFRAIM NYALINGA MICHAEL KOSIA**

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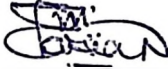
**ABSTRACT**

A study was conducted in the laboratory to assess changes in soil phosphorus fractions in relation to phosphorus sources and to evaluate the influence of those fractions on residual phosphorus availability and uptake of selected nutrients. Residual P was compared to fresh P application at rates of 60 mg P kg<sup>-1</sup> and 180 mg P kg<sup>-1</sup> to determine their influence on dry matter yield (DMY) and the uptake of P, Ca, K, and Mg. Three soils with high P fixing capacity, Sasanda (Umbric Andosol), moderate fixing capacity, Suluti (Rhombic Acrisol) and low fixing capacity, Nkundi (chromic Acrisol) from the Southern highlands of Tanzania were used. A portion of soil (1.0 g) was sequentially extracted with deionized water, 0.5 M sodium bicarbonate (NaHCO<sub>3</sub>), 0.1 M sodium hydroxide (NaOH), 1.0 M hydrochloric acid and a combination of concentrated sulphuric acid and hydrogen peroxide (H<sub>2</sub>SO<sub>4</sub> + H<sub>2</sub>O<sub>2</sub>). Both organic and inorganic P were determined in NaHCO<sub>3</sub> and NaOH extracts. The results indicated that, the release and distribution of various P fractions were dependent on the P source and soil characteristics. In Sasanda and Suluti soils, TSP gave significantly higher effects than MPR on H<sub>2</sub>O-P, 0.5 M NaHCO<sub>3</sub>-P and 0.1 M NaOH-P but opposite results were obtained for HCl-P and H<sub>2</sub>SO<sub>4</sub> + H<sub>2</sub>O<sub>2</sub>-P fractions. The trends of most P fractions in Nkundi soil were opposite of those in Sasanda and Suluti soils except for NaOH-P<sub>o</sub> and H<sub>2</sub>SO<sub>4</sub> + H<sub>2</sub>O<sub>2</sub>-P which were similar. The FeO-P<sub>i</sub> was highest in Nkundi and lowest in Sasanda. The results also showed that high rates of fresh applications of TSP significantly increased DMY while low rates led to only slight increases in DMY over their respective residual

sources. Dry matter yield increased significantly ( $\leq 0.05$ ) at high application rates in Sasanda, while there was only slight increase over low residual application rates of MPR. MPR caused slight increases in DMY and Ca uptake over TSP, and Ca uptake increased with P application rates. Calcium concentration in the plant was at sufficiency level. Potassium concentration in plant was at deficiency level in all soils, and its uptake decreased with an increase in Ca concentration in plants. Phosphorus caused a slight increase in Mg concentration in plants probably due to depressed K uptake. From this study it was concluded that P fractions were influenced by both P sources and soil properties. Minjingu PR had higher residual effect on DMY and uptake of P and Ca than TSP. Phosphorus influenced Ca and Mg nutrition while K decreased with an increased Ca uptake from the soils. The data suggest that maintenance application of P is required in the soils that had residual P. In addition, other nutrients should be calibrated along with P sources to avoid imbalance of nutrients. Further research is required to assess the relationship between P fractions and soluble P forms.

**DECLARATION**

I, Efraim Nyalinga Michael Kosia, do hereby declare to the Senate of the Sokoine University of Agriculture that this dissertation is my own original work and has not been submitted in any other University for a degree award.

Signature.....

Date.....21.05.2003

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## **DEDICATION**

This dissertation is dedicated to El-Shaddai; our all-sufficient God, to Him be all honor and glory now, forever and ever; Amen. I also dedicate it to my beloved father Evangelist Michael N. Kosia and my mother late Prisca Kosia who past away at the beginning of my undergraduate studies; my success is the fruit of their work.

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**LIST OF SYMBOLS AND ABBREVIATIONS**

%	Percentage
µg	Microgram
<	Less than
>	Greater than
°C	Degree celcius
Al	Aluminium
B	Boron
C	Carbon
Ca	Calcium
CaCl <sub>2</sub>	Calcium chloride
CEC	Cation exchange capacity
CL	Clay loam
cm	Centimetre
cmol (+)/kg	Centimole per kilogram
CV	Coefficient of variation
DAS	Days after sowing
DM	Dry matter
DMRT	Duncan's Multiple Range Test
DMY	Dry matter yield
e.g	Example
<i>et al</i>	and others

Fe	Iron
FeO	Iron oxide
G/pot	Gram per pot
h	hour
H <sup>+</sup>	Hydrogen ion
H <sub>2</sub> O	Water
H <sub>2</sub> O <sub>2</sub>	Hydrogen peroxide
H <sub>2</sub> PO <sub>4</sub> <sup>-</sup>	Orthophosphate
H <sub>2</sub> SO <sub>4</sub>	Sulphuric acid
HCl	Hydrochloric acid
HNO <sub>3</sub>	Nitric acid
K	Potassium
K <sub>2</sub> O	Potassium oxide
KCl	Potassium chloride
kg P ha <sup>-1</sup>	Kilogram of phosphorus per hectare
<u>M</u>	Molarity
Mg	Magnesium
ml	Millilitre
mm	Millimetre
MPR	Minjingu phosphate rock
N	Nitrogen
<u>N</u>	normality
Na	Sodium

NaOH	Sodium hydroxide
ns	Not significant
OC	Organic carbon
P	Phosphorus
pH	Negative logarithim of hydrogen ion concentration
P <sub>o</sub>	Organic phosphate
PO <sub>4</sub> <sup>-</sup>	Phosphate ion
PR	Phosphate rock
PRs	Phosphate rocks
P <sub>t</sub>	Total phosphorus
RAE	Relative agronomic effectiveness
RCBD	Randomized complete block design
rpm	Revolution per minute
SA	Sulphate of ammonia
SCL	Sand clay loam
SUA	Sokoine University of Agriculture
TSP	triple superphosphate
Zn	Zinc

## CHAPTER ONE

### 1.0 INTRODUCTION

Phosphorus is one of the essential elements for plant growth and development. It is very stable and immobile within the soil, so it is not easily leached by soil water. Yet, many soils especially those of the tropics and sub-Saharan regions lack sufficient amounts in the form that is readily available to crops to ensure satisfactory growth. Sanchez (1976) pointed out that in soils of the tropics, particularly highly weathered soils, P was known to be the second nutrient limiting crop production after nitrogen.

The biotic availability of soil P has been implicated as a key factor regulating productivity of natural and agricultural ecosystems (Walker and Syers, 1976; Cole and Heil, 1981; Smith, 1992; Crews, 1993; Crews *et al.*, 1995). In addition, many soils in the humid tropics require good P management because only a small fraction of the total P is available for plant uptake. The native P compounds are mostly unavailable for plant uptake, some being highly insoluble. However, phosphorus availability can change rapidly in agricultural ecosystems mainly due to fertilization and changes in soil reaction. Nevertheless, when soluble forms of P are added to soils, they are fixed or changed to unavailable forms and in time react further to become highly insoluble forms.

Other factors reported to contribute to the low available P for plant uptake include P depletion due to crop harvests with no corrective fertilizer input (Palm, 1995) or sub-optimal applications of P fertilizer, erosion of the top soil by runoff (Smaling *et al.* 1993; Swift *et al.*, 1994) and losses by leaching especially in sandy soils (Paton and Loneragan, 1960) followed by its accumulation in B-horizon (Mattingly, 1970). The low plant available P in soils has contributed greatly to declining food production (Shepherd, *et al.*, 1995).

In fact, the use of chemical fertilizers is often considered to be an immediate solution to correct nutrient deficiencies in soils (Woomer *et al.*, 1997). Phosphorus fertilizers applied to correct its deficiency are usually chemically manufactured materials which contain compounds of phosphate that are readily soluble in water. Some phosphate rocks are sufficiently soluble in acid soils to be useful fertilizer materials for some crops.

There are a number of PR deposits in Tanzania some of which are sufficiently reactive to serve as good sources of P (Woomer *et al.*, 1997). In acid soils, PR has been reported to have approached or sometimes exceeded the performance of triple superphosphate (Amberger, 1978). Acid soils that could benefit from PR application are found in various parts of Tanzania (Anderson, 1970). However, transport costs due to poor infrastructure and long distances are likely to limit MPR use when compared to water-soluble sources such as TSP (Szilas, 2002). Thus the best alternative may be to use MPR in areas within a certain distance from the mine depending on transport cost and production economics. According to Szilas (2002),

currently the profitability of MPR is justifiable within a distance of 1000 km from the mine.

Le Mare (1991) reported that, many investigations have been carried out to assess the effectiveness of PRs and that in the past thirty years; the principles controlling their dissolution and availability to crops have been determined. Agronomic effectiveness however, has been reported to vary from one soil to another due to differences in its solubility and other unidentified factors (Smithson *et al.*, 2001).

The agronomic effectiveness of PR is frequently determined from the comparison of PR and soluble P fertilizer at relatively large, one-time applications (Buresh *et al.*, 1997). Large applications of soluble P (Sanchez and Salinas, 1981) or PR (Kumar *et al.*, 1993) can have long-term residual effects on crop yield and P fractions.

Phosphorus fractions may be grouped as water extractable P ( $H_2O$ -  $P_i$ ), sodium bicarbonate extractable inorganic P ( $NaHCO_3$ -  $P_i$ ), sodium bicarbonate extractable organic P ( $NaHCO_3$ -  $P_o$ ), sodium hydroxide extractable inorganic P ( $NaOH$ -  $P_i$ ), sodium hydroxide extractable organic P ( $NaOH$ -  $P_o$ ), hydrochloric acid extractable inorganic P ( $HCl$ -  $P_i$ ) and sulphuric acid and hydrogen peroxide extractable P ( $H_2SO_4/H_2O_2$ -P) referred to as residual P. Soil solution P,  $NaHCO_3$ - $P_i$  and a portion of  $NaHCO_3$ - $P_o$  that is mineralized within one season constitute readily available P. Sodium hydroxide extracts Al-P and Fe-P and a portion of stable soil organic matter associated P considered as active P while  $H_2SO_4/H_2O_2$  extracts apatite minerals considered as inactive P. The undissolved PR that gradually releases easily available

P for up to 10 years represents active P that cannot be detected by sodium hydroxide (NaOH) extraction but can be extracted by hydrochloric acid (HCl).

This knowledge on soil P fractions by chemical means is useful in predicting P availability and plant-uptake. The P source applied either as TSP or MPR has significant effect on the readily available ( $\text{NaHCO}_3\text{-P}_i$ ) and active ( $\text{NaOH-P}_i$ ) P forms. Furthermore, soils that have been fertilized with PR fertilizer contain undissolved PR that is released with time (Kumar *et al.*, 1993). Thus chemical fractionation of soil P can be useful in fertilizer P management.

Despite the beneficial effects of P fractions on P management, very few P fractionation studies have been conducted in Tanzania (Ikerra *et al.*, 2001; Szilas, 2002). Therefore, the overall objective of this study was to assess the changes in soil P fractions as a result of P fertilizer sources and their influence on residual P availability at three sites with slightly acid soils from the southern highlands of Tanzania.

The specific objectives were:

1. To assess the effect of P sources on soil P fractions within the plough layer (0-15cm depth).
2. To assess whether application of relatively high rates of P for three seasons increases P status of soils.
3. To assess the effect of residual P on the uptake of some nutrients.

## CHAPTER TWO

### 2.0 LITERATURE REVIEW

#### 2.1 Native soil phosphorus

The natural abundance of P in the lithosphere averages 0.12% (Catheart, 1980), which is lower than potassium, calcium or magnesium, the other geologically cycled macronutrients (Crews, 1996). Similarly, soils have low P as the parent materials from which they are formed. But generally, total P in soils with respect to parent materials appear to be highest in descending order by those in limestone with intrusion, micaceous schist and quartzite (Singh *et al.*, 1986). This might be due to relatively high phosphate content in igneous and metamorphic rocks as compared to sedimentary rocks like shales, sandstone and limestone (Bear, 1964). However, the vast majority of soil P is present in organic and inorganic forms that are unavailable to the biota (Barber, 1984; Stewart and Tiessen, 1987). Hong-Qing *et al.* (1997) reported highest Ca-P in soils which originated from shale and limestone while Fe-P and occluded-P were associated with soils developed from granite and gneiss.

Smeck (1973) and Walker and Syers (1976) proposed generalised pathways of P transformations over the course of soil development. On average, at the early stage of soil formation that is congruent with ecological primary succession, P is a constituent of minerals (Smeck, 1973). Primary apatite minerals gradually undergo hydrolysis and inorganic P becomes labile. Newly released P is either taken up by

organisms, thus entering the organic P pool ( $P_o$ ), or sorbed onto positively charged colloidal sites of secondary minerals, especially hydroxides of aluminium (Al) and iron (Fe).

Both the organic P and non-occluded inorganic P ( $P_i$ ) pools increase in size as the apatite pool feeding them is solubilized. Once the apatite pool is diminished,  $P_o$  and secondary  $P_i$  pools also begin to decline as P is lost from the soil system through leaching, erosion and in crop harvests (Crews, 1996). Initially a large percentage of soil  $P_o$  and surface bound  $P_i$  are labile, but with time  $P_o$  compounds resistant to microbial breakdown begin to dominate the pool (Stewart and Tiessen, 1987). Meanwhile,  $P_i$  becomes occluded in amorphous or crystalline oxides rendering the vast majority of soil P unavailable to the biota (Crews, 1996).

According to Loganathan and Sutton (1987) highly acidic soils of humid tropics are known to present problems in their management for P fertility. These soils are low in available P and are expected to fix large quantities of added P. Effective P fertility management in these soils requires knowledge of the P status and P sorption properties of the soils. Total P content is primarily a property of a soil and is therefore, not dependent on any other variable. However, the more labile P fractions are dependent upon the chemical and physical properties of the soils but may, at the same time, control other variables, such as organic matter accumulation (Cole and Heil, 1981).

Tiessen *et al.* (1984) reported that highly weathered soils contain low amounts of organic matter and high contents of active sesquioxides. Clay, and to a lesser extent silt contents, are related to low amounts of extractable  $P_i$ , and high residual non extractable P forms. Chemical and physical properties of these soils reflect the range of soil development. The relative abundance of inorganic P forms gives an indication of the degree of chemical weathering of the soils. The strongly weathered soils have higher proportions of inactive inorganic P (occluded P, reductant soluble P, and residual P) forms and Fe-P than other soils (Chang and Jackson, 1957). At low pH values and elevated Al and Fe activities the solubility of secondary  $P_i$  forms are much lowered, and available P is largely controlled by the mineralization of  $P_o$ . In contrast, soils with high pH and high base saturation tend to have lower proportions of P content in extractable organic and inorganic forms, and relatively higher organic acidic extractable P content (Tiessen *et al.*, 1984).

## **2.2. Phosphorus from fertilizer sources**

### **2.2.1 Residual effect of phosphatic fertilizer materials**

Transformation of P into insoluble and unavailable compounds is considered to be primary causes of P fertilizer inefficiency (Chand and Tomar, 1993). Water soluble phosphate fertilizers are generally in readily available form (in soil solution) but are quickly converted to slowly available P called labile P forms. Plants can use these forms at first, but upon ageing they are rendered less available and revert to very slowly available form called non-labile P (Brady, 1990). However, residual effects

from large P applications ( $685 \text{ kg P ha}^{-1}$ ) have been observed on high P fixing soils, in which adequate P was supplied for corn seven years after application (Kamprath, 1967).

In fact, residues of PR and TSP in soil several years after their application can be effective sources of P for plant species that have relatively low external P requirements (Kumar *et al.*, 1994). Soils that have been fertilized with RP fertilizer contain undissolved PR for many years because only a small fraction of the total P dissolves quickly in weeks and the remainder dissolves slowly in terms of years (Kumar *et al.*, 1994). When phosphate rock fertilizer was applied, most of fertilizer P was still present as original apatite in the soil after 5 years, but in contrast, the highest concentration of P from the super phosphate treatment was in the clay-sized fraction (Kumar *et al.*, 1993; Bolland *et al.*, 1994). Therefore, the partitioning of P applied as either MPR or TSP may differ depending on the particle size distribution of the soil.

Phosphate rocks may provide a higher residual effectiveness than super phosphates, which may be an advantage for some management requirements (Hammond, 1972). An interesting feature of less reactive PRs in tropical acid soils is that their agronomic effectiveness relative to soluble fertilizer improves appreciably with time. The superior residual effects of finely ground PRs compared to water soluble fertilizers in the soils result from relative increases over time in the concentration of the plant available P in the soil solution with the PR treatments due to its dissolution and reaction products (Sale and Mokwape, 1993).

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### 2.2.2 Effect of P application on P fractions in soils

Changes in P fractions have been observed with different P sources. Nyambiti *et al.* (2001) observed significant increases in extractable levels of all inorganic P fractions at the end of two growing seasons. The enrichment of all inorganic P fractions indicates that there was an increase in both the readily available and the reserve active inorganic P as reported by Baanante (1997). Hong-Qing *et al.* (1997) observed changes in content of various aluminium forms when phosphate fertilizer was applied to a red upland soil. Others studies have shown increases in Bray-I extractable P (Sharma and Sangrai, 1993), Al-P, Fe-P and Ca-P as a result of P fertilizer application in an alkaline soil (Singaram and Kothandaraman, 1993). In contrast, Kumar *et al.* (1994) working with sandy soils found no significant conversion to secondary forms of P from the forms that were present shortly after fertilization. Large proportions (73-97%) of North Carolina PR and Queensland PR remained in the original form five years after fertilizer application. This suggests that changes to secondary forms of P may be dependent on soil type and clay content. Nyambiti *et al.* (2001) working with two soils reported that clay loam soil (55% clay) had higher conversion of resin  $P_i$  to other  $P_i$  fractions ( $\text{NaHCO}_3\text{-}P_i$  and  $\text{NaOH-}P_i$ ) than sand clay loam soil (35% clay).

In addition P fractionation studies have shown that acid extractable-P levels in soils top-dressed with low rates of reactive phosphate rock (RPR) increased with time, but the amount of alkaline extractable-P decreased. Such decrease in alkaline extractable-P levels in soils where PRs were applied was attributed to plant uptake

of P from Al-P and Fe-P forms (Leinweber *et al.*, 1999). Hong-Qing *et al.* (1997) reported that Al-P and Fe-P were positively correlated with available  $P_o$ .

### **2.2.3 Relationship between P fractions and P availability**

The abundance and activities of the various  $P_i$  forms and the turnover of  $P_o$  control the replenishment of labile resin extractable P following plant uptake (Tiessen *et al.*, 1984). Organic matter acts as a sink as well as a long-term reservoir of P, through controlled mineralization processes (McGill and Cole, 1981). Labile bicarbonate extractable  $P_o$  is easily mineralizable and contributes to plant available P (Browman and Cole, 1978). More stable forms of  $P_o$  which are involved in the long-term transformation of P in soils, can be extracted with hydroxide (Batsula and Krivonosova, 1973). More resistant non-extractable  $P_o$  are extracted by  $H_2SO_4 + H_2O_2$ .

Total inorganic P fractions are divided into active and inactive forms. The former consists of Al-P, Fe-P and Ca-P, and the later consists of occluded, reductant-soluble, and residual P (Chang and Jackson, 1957). The more active forms are the fractions most available to plants, with the degree of availability increasing in the order: Ca-P > Fe-P > Al-P in upland conditions (Thomas and Peaslee, 1973). But like organic matter, the inactive  $P_i$  forms act as the long-term reservoir of P, depending on soil properties such as pH (Murrman and Peech, 1969). The relative abundance of inorganic forms also gives an indication of the degree of chemical

weathering of the soils, strongly weathered soils having a higher proportion of inactive inorganic forms and Fe-P than the others (Chang and Jackson, 1957).

### **2.3 Plant uptake of P from soils**

Reserves of plant-available P in soils come from native P, past fertilization or both (Pothuluri *et al.*, 1991). The major forms of P taken by plants from the soil solution are  $\text{H}_2\text{PO}_4^-$  and  $\text{HPO}_4^{2-}$ . The average soil solution P concentration is about  $0.05 \mu\text{g/g}$  but varies widely among soils. The P concentration required by most plants varies from  $0.003$  to  $0.3 \mu\text{g/g}$  depending on crop species and level of production (Tisdale *et al.*, 1993)

The supply of inorganic P ( $\text{P}_i$ ) to plants depends on the concentration of  $\text{P}_i$  in the soil solution, the quantity of the solid phase  $\text{P}_i$  that serves as a reserve to replenish P in soil solution and the ability of the soil to maintain the solution P concentration (Holford, 1997). Though desorption of  $\text{P}_i$  is smaller than adsorption of  $\text{P}_i$ , a portion of the  $\text{P}_i$  sorbed by Fe and Al oxides can be reversibly released to replenish  $\text{P}_i$  in the soil solution (Barrow, 1983). Desorption of P in a soil is inversely related to the duration of P sorption, soil P-sorption capacity, the amount of soil-sorbing capacity that is unoccupied and content and form of Fe and Al oxides in the soil (Frossard *et al.*, 1995).

Net mineralization of  $\text{P}_o$  is generally directly related to total soil  $\text{P}_o$  for both fertilized and non-fertilized soils (Sharpley, 1985). Net mineralization of  $\text{P}_o$ , tends to

be more important as a source of plant-available P on highly weathered soils such as Oxisols and Ultisols. This is because of the generally greater  $P_o$  in highly weathered soils (Tiessen *et al.*, 1984; Sharpley *et al.*, 1987). Organic P as a source of plant-available P might be an alternative explanation of the poor correlation between crop response to applied P and P extracted by conventional soil P tests that do not assess  $P_o$  (Warren, 1992; Tiessen *et al.*, 1984). Such poor correlation might arise when the mineralization of  $P_o$  supplies sufficient amount of plant available P to match or exceed the shortfall in P releases from labile  $P_i$  to meet plant demand for P.

Browman and Cole (1978) proposed that the sum of bicarbonate  $P_i$  and  $P_o$  would be a better indicator of plant response to P than bicarbonate alone. This was in the case of the soils low or deficient in P based on bicarbonate  $P_i$ . Soils with low bicarbonate  $P_i$  and much higher bicarbonate  $P_o$ , however, can be responsive to P fertilizer (Buresh *et al.*, 1997). But extractable  $P_i$  together with a labile  $P_o$ -to-labile  $P_i$  ratio might be valuable in assessing the importance of mineralization. The relative importance of  $P_o$  mineralization, compared with desorption of  $P_i$ , as a source of plant-available P would presumably be greatest at low extractable  $P_i$ , high labile  $P_o$ -to-labile  $P_i$  ratio, and high microbial P (Buresh *et al.*, 1997). When  $P_o$  supplied available P that was sufficient for plant demand, the combination of an indicator of P availability from  $P_o$  with extractable  $P_i$  did not improve the correlation with plant growth (Mnkeni *et al.*, 1995).

## 2.4 Management of soil phosphorus

The reversion of plant-available to plant-unavailable P is a process that cannot be avoided, but proper management can lead to increase in efficiency of fertilizer P (Penas and Sander, 1993). According to Sanchilli (1965), practices that directly affect the availability of native or applied P include liming, application of manure and crop residues, fertilizer placement, rate, time and frequency of phosphate application; and practices for the control of cropping and soil erosion.

Management intensity influences the content and form of P in soils. Richards *et al.* (1995) reported that resin and  $\text{NaHCO}_3\text{-P}$  were increased by 3% as a result of P fertilizer application. McKeenzie *et al.* (1992) found that labile P fractions were increased to a greater extent by long term application of P than the more stable fractions of P. Furthermore, Jama *et al.* (1997) observed that moderate rates of P ( $10\text{-}20 \text{ kg P ha}^{-1}$ ) could give economic increases in yields and at the same time bring about a gradual build up of the P status of soils.

Other researchers have reported that fertilizer P in arable soils was gradually transformed to  $\text{NaOH-P}$  while in grassland such P remained mostly in readily soluble P fractions (Leinweber *et al.*, 1999). Under grassland, the fertilizer led to increases in the most readily soluble P fractions. The possible explanation was the adsorption of  $\text{H}_2\text{PO}_4^-$  and  $\text{HPO}_4^{2-}$  on pedogenic oxides or its incorporation into stable humic substances in arable soils, whereas under grassland, organic anions from root exudates or microbial metabolites may compete to a large extent with  $\text{HPO}_4^{2-}$  for adsorption sites at pedogenic oxides. Less extensive land uses such as reforestation,

permanent fallow or alternative cropping has resulted in the decrease of total phosphorus ( $P_t$ ) and greater percentage in less soluble forms. However, the intensively managed soils have significantly greater amounts and proportion of water-P, resin and bicarbonate-P (Leinweber *et al.*, 1999).

Presence of such knowledge on P fractions present at any time may provide basic information, which may be useful in corrective and maintenance applications of P to increase crop production, prevent environmental degradation, and avoid unnecessary costs.

## **2.5 Phosphorus fractionation procedures**

Dean (1938) initiated characterization of the forms of inorganic phosphates in soils by sequential extraction with acid and alkali reagents while Ghani (1943) and Williams (1950) used modified versions of his scheme. Ammonium fluoride was subsequently introduced (Chang and Jackson, 1957) to distinguish between Al and Fe bound P. The information about P fractions is useful in predicting bioavailability of P in soil as well as predicting the likelihood of its transport (Sui *et al.*, 1999).

Several researchers (Robertson *et al.*, 1966; Rajan, 1983; Chien *et al.*, 1987, Rajan *et al.*, 1991) have reported that the fractionation procedure of Chang and Jackson (1957) or its modification may provide reliable estimates of the residual PR in the soil and other forms of P associated with soil materials. However, the P fractionation procedure developed by Hedley *et al.* (1982) and Tiessen *et al.* (1984) has been the most commonly used procedure in the last ten years. The procedure extracts both  $P_i$

and  $P_o$ . It extracts the most available chemically bound pool of P first, followed by pools of decreasing availability (Sui *et al.*, 1999) and ending with the more resistant forms of P. Sui *et al.* (1999) reported that  $P_i$  fractions extracted include resin,  $\text{NaHCO}_3$ , microbial, NaOH, NaOH after sonication, HCl and residual, while  $P_o$  fractions include  $\text{NaHCO}_3$ , microbial, NaOH, NaOH after sonication and residual  $P_o$ .

The resin-extractable  $P_i$  is thought to be the most available P fraction to plants (Amer *et al.*, 1955; Sibbesen, 1977). However, more recently Sui *et al.* (1999) suggested that deionised water extractable P might be a proper representative of the most bio-available  $P_i$ . The  $\text{NaHCO}_3$ -extractable  $P_o$  and  $P_i$  fractions constitute labile pools and are readily available to plants. Buresh *et al.* (1997) proposed that these labile P fractions (Resin P and  $\text{NaHCO}_3$ ) which become available for plant uptake within one season are referred as liquid P. Therefore, only that portion of  $\text{NaHCO}_3$ - $P_o$  that is mineralized within one season, would represent liquid P from  $\text{NaHCO}_3$ - $P_o$ . Sodium bicarbonate at pH 8.5 extracts the most easily mineralizable pool of  $P_o$ , consisting of organic compounds like ribonucleic acid, glycerophosphate and some microbial P, which contribute to plant available P (Browman and Cole, 1978; Anderson, 1980). It also extracts  $P_i$  (referred to as Bic-  $P_i$ ) which is part of the labile P fraction (Olsen *et al.*, 1954). This labile inorganic pools are thought to originate from P adsorbed on surfaces of sesquioxides or carbonates (Mattingly, 1975).

Sodium hydroxide extractable  $P_i$  and  $P_o$  fractions are moderately labile. The fractions released are those physically protected as  $P_o$  and  $P_i$  (Hedley *et al.*, 1982).

Frossard *et al.* (1989) pointed out that NaOH extractable inorganic phosphates are more strongly bound to Fe and Al hydroxides and clay surfaces. These may be considered 'retained  $P_i$ ' (Hsu, 1989) or capital P (Buresh *et al.*, 1997) that could be biologically active in future. The  $P_o$  removed by NaOH has for sometimes been considered as relatively stable with slow turnover rates. Tiessen *et al.* (1984) suggested that this fraction may include some relatively labile  $P_o$  associated with cellulose. The more stable NaOH- $P_o$  is likely to originate from humic compounds or possibly from inositol phosphates sorbed to Al and Fe hydroxides (Anderson, 1980).

Hydrochloric acid dissolves primary apatite minerals (Williams *et al.*, 1980), and calcium phosphate (Ca-P) secondary minerals (Sui, *et al.*, 1999). These include a portion of PR-P added to soil that becomes available for plant uptake over a number of cropping seasons.

Phosphorus released in the final  $H_2SO_4 + H_2O_2$  digestion is termed residual phosphorus (Residual-P), and is likely to consist of  $P_i$  thoroughly occluded by sesquioxides (Mattingly, 1975),  $P_i$  in resistant primary minerals (Syers *et al.*, 1969), and non-extractable very stable  $P_o$ , probably associated with humic and fluvic acids and sesquioxide-stabilized inositols, among other compounds. Generally, this pool may contain both  $P_i$  and  $P_o$  that are very resistant to decomposition and is related to the pools of rapid and slow recycling organic matter and allow the detection of changes in phosphorus-cycling within an intermediate time frame (Daroub *et al.*, 2000).

## CHAPTER THREE

### 3.0 MATERIALS AND METHODS

#### 3.1 Soil sampling and sample preparation

Six composite soil samples were collected from three selected maize growing sites that had been fertilized with triple super phosphates or Minjingu phosphate rock at the rate of 120 kg P ha<sup>-1</sup> per season for three seasons. Another composite soil sample was collected from absolute control plots of each site, making up nine composite sample collected. The soils from absolute control plots were used for fresh applications of either MPR or TSP whereas those with previous P applications were used for assessment of residual P effects. The composite samples were air-dried and ground to pass through a 6-mm sieve for a pot experiment. In addition, a sub-sample of one kilogram for each treatment from each site was ground to pass through a 2-mm sieve for laboratory analysis.

#### 3.2 Pot experiment

Three composite topsoil (to depth of 15 cm) samples from each site were taken for a pot experiment. Four kilograms of each composite soil was weighed into a clean five litre plastic pot. Eight treatments designated as shown in Table 1 were tested:

**Table 1. Treatments tested in the pot experiment**

Serial No.	Treatment designation (mg P kg <sup>-1</sup> )	Description of the treatments
1	P <sub>0</sub> N <sub>0</sub> K <sub>0</sub> Zn <sub>0</sub>	no nutrient was applied (absolute control)
2	P <sub>0</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub>	received adequate levels of N, K and Zn but no P (P treatment control)
3	P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub>	as treatment 2 but soil was taken from plots which had received P at 120 kg P ha <sup>-1</sup> per season from TSP for three seasons i.e. total of 360 kg P ha <sup>-1</sup> for three seasons.
4	P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub>	as treatment 3 except that the source of P was MPR
5	P <sub>60</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub>	as treatment 2 plus 120 kg P ha <sup>-1</sup> fresh application of TSP.
6	P <sub>60</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub>	as treatment 5 except that the source of P was MPR
7	P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub>	as treatment 2 plus 360 kg P ha <sup>-1</sup> fresh application of TSP.
8	P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub>	As treatment 7 except that the source of P was MPR

The absolute control treatment was intended to evaluate maize dry matter (DM) yield and P uptake under natural soil fertility status while the treatment control was for evaluating the DM yield and uptake under optimum levels of N and K but without P from external sources. Boron ( $2 \text{ g B kg}^{-1}$  soil) was added to Sasanda soil in addition to N, P and K because the soil is known to have low levels of boron. Nutrient sources other than N were thoroughly mixed with the soil samples before sowing. The treatments were replicated three times and arranged in a randomized block design in the glasshouse.

The soil was moistened to 90% of field capacity and equilibrated for one day before sowing. The amounts of water applied to moisten soils to 90% of field capacity were 640 ml, 1570 ml and 540 ml for Nkundi, Sasanda and Suluti soils, respectively.

Six seeds were sown in each pot. Seedlings were thinned to two plants per pot, 14 days after sowing (DAS). The first dose of N was applied at 14 DAS and the second dose of N was applied at 28 DAS. The plants were grown for 42 days after which shoots were harvested by cutting at 1 cm above the soil surface. Shoots were dried at  $65^{\circ}\text{C}$  to constant weight.

### **3.3 Laboratory analysis**

#### **3.3.1 Routine soil analysis**

Physico-chemical properties of each composite sample were determined. All the soil samples were analyzed for particle size distribution, soil pH, cation exchange capacity (CEC), exchangeable bases (Ca, Mg, K, Na) and organic carbon.

Particle size analysis was determined by the hydrometer method after dispersing the soil samples in sodium hexametaphosphate solution (National Soil Service, 1987). Soil textural classes were determined using the USDA textural class triangle (USDA, 1995). Soil pH was determined using a pH electrode in a 1:2.5 soil: water suspension as described by Page *et al.* (1982).

Cation exchange capacity was determined by using the ammonium acetate saturation method (National Soil Service, 1987). Exchangeable Ca and Mg in the ammonium acetate leachate were determined by atomic absorption spectrophotometry, and exchangeable K and Na were determined using the flame photometer method.

Organic carbon was determined by the Walkey and Black method as described by Page *et al.* (1982). Total nitrogen was determined by the semi-micro Kjeldahl procedure (Page *et al.*, 1982).

### 3.3.2 Extractable phosphorus

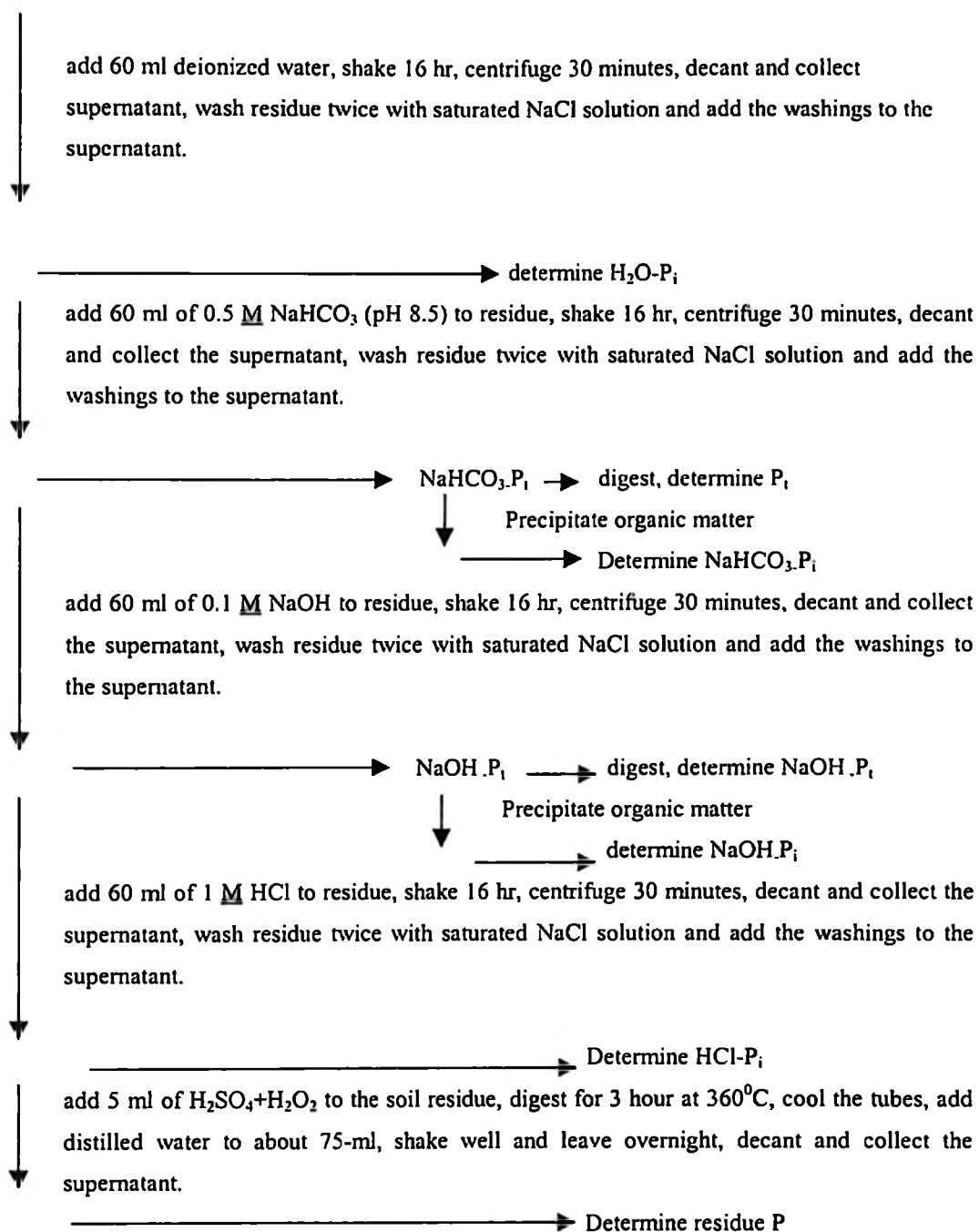
Extractable P in air-dry soils was determined using the iron impregnated filter paper strip method designated as the  $P_i$  method. The iron oxide impregnated filter paper strips were prepared as described by Myers *et al.* (1997) with some modifications recommended by Habib *et al.* (1998). The method of iron oxide-impregnated paper using 0.01 M  $\text{CaCl}_2$  was not used because it underestimates P from the phosphate treated soils (Myers *et al.*, 1997). Working with the same soils, Habib *et al.* (1998) modified the methodology by using 0.02 M  $\text{KCl}$  instead of 0.01 M  $\text{CaCl}_2$  and found that the  $P_i$ -P with  $\text{KCl}$  was more closely related to P uptake with both PR and TSP treated soils.

The  $P_i$  paper strips were shaken with soil samples suspended in 0.02 M  $\text{KCl}$  solution on a reciprocating shaker for 16 hours at 175 rpm. The  $P_i$  strips were then taken out and washed free of soil using distilled water and air-dried. Air-drying of the wet papers before dissolving the sorbed P in dilute acid eliminates the small increase in fluid volume associated with wet paper strips. The P sorbed by the paper strip was dissolved in 40 ml of 0.1 M  $\text{H}_2\text{SO}_4$  by shaking in an Erlenmeyer flask on a reciprocating shaker at 100 rpm for 1 h. After shaking, an aliquot was withdrawn from the flasks and 0.1 M  $\text{NaOH}$  was used to neutralize the acidity while p-nitrophenol was used as the colour indicator. Sodium hydroxide was added drop by drop until yellow colour appeared, then 1.2 M  $\text{H}_2\text{SO}_4$  was added until the yellow colour just faded. The  $P_i$  method using Fe oxide impregnated paper was chosen because it has given good results with both soluble P-fertilized soils and PR-fertilized soils (Sharpley *et al.*, 1994).

### 3.3.3 Fractionation of Soil Phosphorus

A modification of the methods (Figure 1) of Hedley *et al.* (1982), Tiessen and Moir (1993) and Sui *et al.* (1999) was used to extract empirically defined pools of P. A portion of soil weighing 1.0 g was sequentially extracted with 60 ml each of deionized water, 0.5 M NaHCO<sub>3</sub> (pH 8.5), 0.1 M NaOH and 1 M HCl. Each extraction was run for 16 h on reciprocal platform shaker. After each extraction the tubes were centrifuged at 5000 rpm for 30 minutes at room temperature. The supernatant was then decanted, and soil residues were washed twice using 20 ml of saturated sodium chloride (NaCl). The washings were added to the decanted supernatant to make up to 100 ml ready for P determination. After the final extraction, residual P was determined in the soil material left in the centrifuge tubes by extraction with H<sub>2</sub>SO<sub>4</sub> + H<sub>2</sub>O<sub>2</sub> (Tiessen and Moir, 1993). Soil residues from the centrifuge tubes were transferred into digestion tubes, using as little distilled water as possible to reduce time to evaporate water down to around 5 ml in all tubes (Okalebo *et al.*, 1993). Slowly 5 ml of concentrated H<sub>2</sub>SO<sub>4</sub> was added while swirling so that the suspension was well mixed. After cooling, H<sub>2</sub>O<sub>2</sub> was carefully added. The sample was digested at 360<sup>0</sup>C for the time it takes the suspension to turn white, plus 1 hour. The tubes were cooled, made up to 75 ml with distilled water, shaken well and left overnight (Okalebo *et al.*, 1993).

1.0 g soil in 100 ml plastic bottle



**Figure 1. Sequential P fractionation scheme [modified from that of Hedley *et al.* (1982) and Tiessen and Moir (1993)].**

Digestion of bicarbonate and sodium hydroxide extracts was done for determination of total P ( $\text{NaHCO}_3\text{-P}_t$  and  $\text{NaOH-P}_t$ , respectively) in the extracts. Five-milliliter of bicarbonate and two milliliters of sodium hydroxide extracts were pipetted into labelled Pyrex test tubes. Ammonium persulphate oxidizing solution was added to each test tube at the same volume as extracts. The test tubes were covered with aluminium foil, placed in Pyrex beakers and then autoclaved for 90 minutes at 15 psi and  $121^\circ\text{C}$ . After 90 minutes, the steam was turned off; the autoclave depressurized by leaking and then cooled before P was determined colorimetrically.

Undigested extracts were used for determination of inorganic P fractions. Organic P fractions in  $\text{NaHCO}_3$  and  $\text{NaOH}$  extracts were determined by subtracting  $\text{NaHCO}_3\text{-P}_i$  and  $\text{NaOH-P}_i$  from  $\text{NaHCO}_3\text{-P}_t$  and  $\text{NaOH-P}_t$ , respectively.

This procedure differed from the standard Hedley fractionation procedure in that; water was used as the first extractant instead of equilibrating the soil sample with an anion-exchange resin. Sui *et al.* (1999) suggested that using water as a first extractant was intended to extract the most labile P in the soil which may be more closely related to bio-available P in surface run off and leachate from the topsoil than would the resin exchangeable P. The  $\text{P}_i$  method was used to extract labile P from the soil samples to be studied. Some studies showed that anion-exchange resin was not required to extract detectable levels of labile P from the soil samples (Sui *et al.*, 1999).

### 3.3.4 Plant Analysis

The samples were weighed, ground with a cyclone sample mill, and sieved through a 1-mm sieve ready for plant analysis. Leaf samples were analysed for P, K, Ca and Mg. For each plant sample, 1.5 g was ashed in a muffle furnace at 525<sup>0</sup>C for three hours after which the ash was dissolved in 6 N HCl, filtered and aliquots made up to 50 ml with deionized water. This solution was used for the determination of P, K, Ca and Mg. Phosphorus was determined by colorimetric method. Potassium was analysed using a flame photometer while Ca and Mg in the extracts were analysed using an atomic absorption spectrophotometer.

### 3.4 Statistical analysis

The effects of TSP and MPR on P fractions were determined by subtracting values of the absolute control from those from either TSP or MPR treated soils. Thereafter, the values of the increase in extractable P fractions obtained were analysed using paired t-test (Mutuo *et al.*, 1999) to compare the effect of MPR and TSP applications on changes in soil P fractions.

Data of dry matter yield (DMY), plant uptake and concentration of P, K, Ca and Mg in response to P application from different P fertilizer sources were subjected to analysis of variance and treatment means separated by Duncan's Multiple Range Test using MSTATC Program.

The relative agronomic effectiveness (RAE) values were computed using yield data according to the formula described by Engelstad *et al.* (1974), viz.:

$$\text{RAE} = (Y_f - Y_c / Y_r - Y_c) \times 100.$$

Where:

$Y_f$  = Yield due to the tested fertilizer (P as MPR).

$Y_r$  = Yield due to reference fertilizer (P as TSP).

$Y_c$  = Yield obtained in the P control treatment (No P applied)

## CHAPTER FOUR

### 4.0 RESULTS AND DISCUSSION

#### 4.1 Physico-chemical properties of experimental soils

The data pertaining to some physico-chemical properties of Sasanda (Umbric Andosol), Suluti (Rhodic Acrisol) and Nkundi (Chromic Acrisol) soils are presented in Table 2. Their respective pH in water ranged from 5.1-5.4, 5.7-5.8 and 5.1-5.5. Of these, the soils used for fresh MPR and TSP application in pot experiment had pH of 5.2, 5.7 and 5.5 for Sasanda, Suluti and Nkundi respectively. Minjingu PR increased pH in Sasanda and Suluti soils after three seasons of cultivation. This is consistent with others researchers (Hong-Qing *et al.*, 1997) who found an increase in soil pH as a result of MPR application. However, soil pH declined when MPR was applied in Nkundi soils.

On the other hand, soil pH was not affected by TSP application in Suluti and Nkundi soils whereas in Sasanda TSP slightly decreased soil pH. During the three seasons of cultivation, sulphate of ammonium was applied (as a source of nitrogen) along with either TSP or MPR to the three soils. An application of sulphate of ammonium fertilizers has an acidifying effect on soil equal to about 2.5 kg of lime per 0.45 kg of nitrogen (Jones, 1987) which is a ratio of 5.6:1.

**Table 2. Some chemical and physical properties of experimental soils**

Soil Property	Soil type								
	Sasanda soil			Suluti soil			Nkundi soil		
	P <sub>0</sub>	TSP <sub>1</sub>	MPR <sub>1</sub>	P <sub>0</sub>	TSP <sub>2</sub>	MPR <sub>2</sub>	P <sub>0</sub>	TSP <sub>3</sub>	MPR <sub>3</sub>
PH (H <sub>2</sub> O)	5.2	5.1	5.4	5.7	5.7	5.8	5.5	5.5	5.1
OC (%)	3.4	3.5	3.4	1.0	1.0	1.1	2.0	2.0	2.0
Total N(%)	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1
CEC {cmol(+) kg <sup>-1</sup> }	31.1	28.6	32.8	3.0	4.3	5.1	5.4	4.4	5.4
Exch.cations {cmol(+) kg <sup>-1</sup> }									
Ca <sup>2+</sup>	1.9	2.4	3.2	2.4	3.2	3.7	2.8	2.5	3.2
Mg <sup>2+</sup>	0.3	0.2	0.2	0.3	0.2	0.3	0.7	0.3	0.5
K <sup>+</sup>	0.4	0.4	0.3	0.1	0.4	0.2	0.1	0.1	0.2
Na <sup>+</sup>	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.3
Particle size analysis									
%Sand	55.9	53.6	55.2	64.6	67.0	64.6	76.8	79.1	76.8
%Silt	20.1	24.8	20.4	6.1	6.2	6.1	6.4	4.1	4.0
%Clay	24.0	21.6	24.4	29.3	26.8	29.3	16.8	16.8	19.2
Textural Class	SCL	SCL	SCL	SCL	SCL	SCL	SL	SL	SL

No P<sup>1</sup>: No P, N or any other nutrients applied.

TSP<sup>1</sup>: Received adequate levels of N, Cu, Zn, Mg and P (as TSP) during three season of cultivation

MPR<sup>1</sup>: Received adequate levels of N, Cu, Zn, Mg and P (as MPR) during three season of cultivation

TSP<sup>2</sup>: Received adequate levels of N, K, Cu, Zn and P (as TSP) during three season of cultivation

MPR<sup>2</sup>: Received adequate levels of N, K, Cu, Zn and P (as MPR) during three season of cultivation

TSP<sup>3</sup>: Received adequate levels of N, K, Cu and P (as TSP) during three season of cultivation

MPR<sup>3</sup>: Received adequate levels of N, K, Cu and P (as MPR) during three season of cultivation

Therefore, the decline in soil pH where TSP or MPR was applied for three seasons could have been due to  $H^+$  released as a result of nitrification processes. Exchangeable Ca, Mg and K values in the three soils before and after three years of cultivation and fertilization were determined to assess the effect of cultivation and fertilization on those exchangeable cations. After three years of fertilization and cultivation, Ca ranged from 1.9-3.2, 2.4-3.7 and 2.0-3.2  $cmol(+) kg^{-1}$  for Sasanda, Suluti and Nkundi, respectively. But exchangeable Ca in three soils at the beginning of the three years of cultivation and fertilization ranged from 0.6-1.2  $cmol(+) kg^{-1}$  (Szilas, 2002). Therefore, both P sources increased exchangeable Ca in soils. However, MPR caused higher increase in Ca concentration than TSP. This was caused by higher content of Ca in MPR than that in TSP. Triple super phosphate and MPR have Ca contents of 12-14 and 33%, respectively. Superiority of PR over TSP in supplying Ca in soils was also reported by Hong-Qing *et al.* (1997).

Magnesium ranged from 0.2-0.3  $cmol(+) kg^{-1}$  for Sasanda and Suluti while it ranged from 0.3-0.7  $cmol(+) kg^{-1}$  in Nkundi soils. Their respective values before the three years of cultivation and fertilization were 0.6 and 0.7  $cmol(+) kg^{-1}$ . Magnesium was applied to supplement its deficiency in Sasanda soil. However, after three seasons exchangeable Mg declined in the three soils. In contrast, Hong-Qing *et al.* (1997) reported that Mg content in the soil was increased following MPR application. Lower Mg content in fertilized than unfertilized soils was probably due to high uptake of Mg from the soils as a result of higher plant growth in fertilized soils than unfertilized soils during the past three years.

Potassium ranged from 0.3-0.4, 0.1-0.4 and 0.1-0.2 cmol (+) kg<sup>-1</sup> for Sasanda, Suluti and Nkundi respectively. The values of exchangeable K before the three years of cultivation and fertilization were 0.3 for Suluti and Nkundi while it was 0.9 cmol(+) kg<sup>-1</sup> in Nkundi soils. During the three years of cultivation 100 kg K ha<sup>-1</sup> were applied in Suluti and Nkundi soils. However, like exchangeable Mg, K content declined after three years of cultivation and fertilization. These declines in Mg and K content in soils indicate depletion of these nutrients as a results of P fertilization. The cations exchange capacity of soils ranged from 28.6-32.8, 3.0-4.3 and 4.4-5.4 cmol(+) kg<sup>-1</sup> for Sasanda, Suluti and Nkundi soil, respectively. The increase in CEC in Suluti and Nkundi soils for both TSP and MPR applications, and in Sasanda where MPR was applied might be due to cations released from the fertilizer materials applied during the three years of cultivation.

Organic carbon and N contents of the soils were not affected by three years of cultivation and fertilization. The textural classes of the soils were sand clay loam, sand clay loam and sand loam for Sasanda, Suluti and Nkundi soil, respectively. Organic carbon of soils ranged from 3.4-3.5% for Sasanda while Suluti and Nkundi had 1.0 and 2.0% recspectively. Total N in soils was 0.1% for Suluti and Nkundi, and 0.3% for Sasanda.

#### 4.2 Phosphorus fractions in the control soils

The amount of sequentially and non-sequentially extractable P from three sites that have been cultivated for three seasons without fertilization are presented in Table 3. The amount of water extractable P, 0.5 M sodium bicarbonate extractable inorganic P, 0.5 M sodium bicarbonate extractable organic P, 0.1 M sodium hydroxide extractable inorganic P, 0.1 M sodium hydroxide extractable organic P, 1.0 M hydrochloric acid extractable P and concentrated sulphuric acid plus hydrogen peroxide P ranged from 3.1 to 5.2, 17.1 to 36.0, 5.0 to 16.7, 40.8 to 116.8, 18.8 to 108.8, 22.6 to 33.0 and 106.4 to 134.0 mg P kg<sup>-1</sup> soil, respectively. The amount of FeO-impregnated paper P which was determined in non-sequential extraction ranged from 0.4 to 7.4 mg P kg<sup>-1</sup> soil.

Readily available P (H<sub>2</sub>O-P<sub>i</sub> + NaHCO<sub>3</sub>-P<sub>i</sub>) contents were 41.2, 30.2 and 20.2, mg P kg<sup>-1</sup> for Nkundi, Suluti and Sasanda soils, respectively. This indicates that Nkundi soils had high potential to supply P from the native soil. This in agreement with the standard P requirement of these soils which was reported to be 1580, 89 and 77 kg P ha<sup>-1</sup> for Sasanda, Suluti and Nkundi, respectively (Szilas, 2002). However, their respective extractable P as determined non-sequentially by FeO-impregnated paper (FeO-P<sub>i</sub>) was 0.4, 7.4, 2.1 mg P kg<sup>-1</sup>.

**Table 3. Sequentially and non-sequentially (FeO-P) extractable P fractions from the soils that had been cultivated for three seasons without fertilization.**

Phosphorus fraction	Soil extractable P in mg kg <sup>-1</sup> soil		
	Sasanda	Suluti	Nkundi
H <sub>2</sub> O-P <sub>i</sub>	3.1	5.2	5.2
NaHCO <sub>3</sub> -P <sub>i</sub>	17.1	25.0	36.0
NaHCO <sub>3</sub> -P <sub>o</sub>	10.8	16.7	5.0
NaOH-P <sub>i</sub>	116.8	68.8	40.8
NaOH-P <sub>o</sub>	108.8	49.8	18.8
HCl-P <sub>i</sub>	26.4	33.0	22.6
H <sub>2</sub> SO <sub>4</sub> + H <sub>2</sub> O <sub>2</sub> -P	120.3	134.0	106.4
Total-P	403.3	332.5	234.7
NaHCO <sub>3</sub> -P <sub>i</sub>	27.9	41.7	41.0
NaOH-P <sub>i</sub>	225.6	118.6	59.6
FeO-P <sub>i</sub>	0.4	7.4	2.1

These results are in agreement with Szilas (2002) who reported that Suluti had sufficient available P at the beginning of the experiment as determined by both Bray 1 and Olsen method (34 mg P kg<sup>-1</sup> and 11 mg P kg<sup>-1</sup>, respectively). Sasanda (18 mg P kg<sup>-1</sup>) and Nkundi (13 mg P kg<sup>-1</sup>) soils were reported to have intermediate levels of P as determined by Bray 1. However, on the basis of Olsen method (Szilas, 2002) rated Sasanda and Nkundi soils to be deficient in P (Olsen P = 3 mg P kg<sup>-1</sup>).

The hydroxide extractable P reveals that moderate labile P was highest in Sasanda and lowest in Nkundi, which may imply that Fe and Al oxides may have greater influence on P fixation in Sasanda than the other soils. However, acid and residual P did not vary greatly in the three soils.

#### **4.3 Effects of P sources on extractable P fractions at three sites**

The relative increase (over the absolute control) in sequentially extractable P from three sites on which P was applied at 120 kg P ha<sup>-1</sup> per year for three seasons as either TSP or MPR is presented in Table 4 while amounts of sequentially extractable P are presented Appendix 1.

Table 4. Increase in Sequentially and non-sequentially (FeO-P<sub>i</sub>) extractable P fractions following three years' application of either TSP or MPR at 120 kg ha<sup>-1</sup> in three soils

P fractions	Increase in extractable (P mg kg <sup>-1</sup> soil)											
	Sasanda Soil				Suluti Soil				Nkundi Soil			
	TSP	MPR	Difference	TSP	MPR	Difference	TSP	MPR	Difference	TSP	MPR	Difference
H <sub>2</sub> O-P <sub>i</sub>	6.9	3.2	ns	30.8	12.7	*	20.5	30.3	*			
NaHCO <sub>3</sub> -P <sub>i</sub>	30.5	17.8	*	106.8	44.5	ns	18.5	45.5	ns			
NaHCO <sub>3</sub> -P <sub>o</sub>	28.5	0.3	ns	14.5	12.9	ns	21	13.4	ns			
NaOH-P <sub>i</sub>	196.1	110.6	ns	72.1	36.7	ns	17.0	32.7	*			
NaOH-P <sub>o</sub>	23.1	46.0	*	63.6	2.7	ns	22.5	45.6	ns			
HCl	5.4	42.2	*	69.7	144.8	ns	82.7	6.3	*			
H <sub>2</sub> SO <sub>4</sub> -P <sub>i</sub>	-0.1	70.5	ns	12.5	110.6	*	24.9	27.1	ns			
Total-P	290.2	198.6	*	370.1	365	ns	207.1	200.8	ns			
NaHCO <sub>3</sub> -P <sub>i</sub>	58.8	17.9	*	121.3	57.4	ns	39.5	58.9	ns			
NaOH-P <sub>i</sub>	219.1	64.6	ns	136.5	40.2	*	39.5	78.3	ns			
FeO-P <sub>i</sub>	3.3	2.8	ns	64.3	26.7	*	69.8	36.4	*			

The increase in water extractable P, 0.5 M sodium bicarbonate extractable inorganic P, 0.5 M sodium bicarbonate extractable organic P, 0.1 M sodium hydroxide extractable inorganic P, 0.1 M sodium hydroxide extractable organic P, 1.0 M hydrochloric acid extractable P and concentrated sulphuric acid + hydrogen peroxide P ranged from 3.2 to 30.8, 17.8 to 106.8, 0.3 to 28.5, 17.0 to 196.1, -46.0 to 63.6, 5.4 to 144.8 and -0.1 to 110.6 mg P kg<sup>-1</sup> soil, respectively. The increase in FeO-impregnated paper, which was determined in non-sequential extraction, ranged from 2.8 to 69.9 mg P kg<sup>-1</sup> soil.

In Sasanda soil, TSP had relatively higher influence than MPR on labile (H<sub>2</sub>O-P<sub>i</sub> and NaHCO<sub>3</sub>-P<sub>i</sub> and NaHCO<sub>3</sub>-P<sub>o</sub>) and moderately labile P (NaOH-P<sub>i</sub> and NaOH-P<sub>o</sub>) fractions, but only NaOH-P<sub>i</sub> was significantly ( $P \leq 0.05$ ) higher in TSP than in the MPR treatment. This indicates higher P solubility of TSP than MPR in this soil which may reflect the difference of these two sources in supplying plant available P. These observations are in agreement with Buresh *et al.* (1997) who reported that P from water-soluble sources (eg TSP) is rapidly released to labile soil P and then to moderately labile P as determined by NaOH-P<sub>i</sub>.

Application of inorganic P fertilizers can increase bicarbonate and hydroxide P when the rate of P addition exceeds P uptake by plants (Beck and Sanchez, 1996; Schmidt *et al.*, 1996; Linguist *et al.*, 1997) thereby contributing to readily available and capital P (Buresh *et al.*, 1997). But the P in most PRs, is only slowly released in acid soils resulting in gradual build up of NaOH-P<sub>i</sub>, thus more time is required to build up bicarbonate and hydroxide P<sub>i</sub> from MPR than TSP treated soil.

In this soil the results further reveal that NaOH-P<sub>i</sub> was the main sink for applied P either in the form of TSP (67.6%) or MPR (55.7%). Similar results were reported by Buehler *et al.* (2002) who observed that resin-P<sub>i</sub>, NaHCO<sub>3</sub>-P<sub>i</sub> and NaOH-P<sub>i</sub> increased with P fertilizer input, with the NaOH-P<sub>i</sub> fraction being the main sink for applied P. These results suggest that the transfer of different P fractions determined in sequential extraction was strongly dependent on the degree of P saturation of soil Al and Fe hydroxides. Sodium hydroxide P<sub>i</sub> consists of Fe-oxide and Al-oxide associated P<sub>i</sub> (Williams and Walker, 1969). When this fraction is determined by sequential extraction, it presumably includes soil P capital because it is a sink for soluble P fertilizer added in excess of plant uptake, and is a subsequent source of plant-available P (Beck and Sanchez, 1994; Schmidt *et al.*, 1996).

Minjingu PR was more effective than TSP in increasing acid extractable P (HCl-P<sub>i</sub> and H<sub>2</sub>SO<sub>4</sub> + H<sub>2</sub>O<sub>2</sub>-P). Acid extractable P (HCl-P<sub>i</sub>) gave no significant difference between MPR (42.2 mg kg<sup>-1</sup>) and TSP (5.4 mg kg<sup>-1</sup>) treated soils. Statistical difference was probably masked by high variability within the treatments. Magid and Nielsen (1992) also reported high variability of repeated measurements of NaHCO<sub>3</sub>-P<sub>o</sub> and NaOH-P<sub>o</sub>.

However, figures of MPR (42.2 mg kg<sup>-1</sup>) and TSP (5.4 mg kg<sup>-1</sup>) treated soils suggests that some of the P applied as MPR remained in the soil as originally applied apatite [Ca<sub>6</sub>(PO<sub>4</sub>)<sub>3</sub>Ca(OH)<sub>2</sub>]. The HCl fraction, estimates active soil P<sub>i</sub> in undissolved PR that can supply plant-available P (Buresh *et al.*, 1997). Furthermore, results of H<sub>2</sub>SO<sub>4</sub> + H<sub>2</sub>O<sub>2</sub> extractable P (-0.1 and 70.1 mg P kg<sup>-1</sup> soil) from TSP and

MPR treated soils respectively, suggest that MPR may contain some fraction of P that was not extractable with HCl, thus contributing to residual P ( $\text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2\text{-P}$ ) while all the applied water soluble TSP-P was extractable by HCl, thus  $\text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2$  was unable to detect increase in P fractions. It is important to note that the sums of the increase in HCl-P and  $\text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2\text{-P}$  were  $5.3 \text{ mg kg}^{-1}$  and  $112.7 \text{ mg P kg}^{-1}$  for TSP and MPR treated soils, respectively. This implies that a substantial amount ( $112.7 \text{ mg P kg}^{-1}$  soil) of the applied P ( $180 \text{ mg P kg}^{-1}$ ) as MPR over the three years' period did not dissolve in this soil while most of the dissolved P was fixed and hence not readily available for plant uptake.

Like other inorganic plant available extractable P ( $\text{H}_2\text{O-P}_i$  and  $\text{NaHCO}_3\text{-P}_i$ ), iron oxide impregnated paper ( $\text{FeO-P}_i$ ) extracted from TSP applied soil was slightly higher than that extracted from MPR applied soils. Non statistical significant difference as a result of TSP and MPR applications for the organically extractable P ( $\text{NaHCO}_3\text{-P}_o$  and  $\text{NaOH-P}_o$ ) was due to high variability within the treatments. Magid and Nielsen (1992) also reported high variability of repeated measurements of  $\text{NaHCO}_3\text{-P}_o$  and  $\text{NaOH-P}_o$ .

Net negative organic extractable P was observed where MPR has been applied. These results are similar to those of Nyambiti (2001). Depletion of the labile  $\text{P}_o$  in the MPR treated soils (Nyambiti *et al.*, 2001) was reported to be caused by mineralization of organic P forms (Rajan *et al.*, 1996). In contrast, Mutuo *et al.* (1999) reported that bicarbonate and hydroxide P were unaffected by P treatments. The net negative sodium hydroxide  $\text{P}_o$  ( $-46.0 \text{ mg P kg}^{-1}$ ) in Minjingu PR treated

Sasanda soil was probably due to slow release of P with time. This agrees with Duxbury *et al.* (1989) who proposed that mineralization of phosphate esters is regulated by the demand for nutrients.

In Suluti soil, results followed similar trends as those in Sasanda soil. TSP had relatively higher influence than MPR on labile ( $\text{H}_2\text{O}-\text{P}_i$  and  $\text{NaHCO}_3-\text{P}_i$  and  $\text{NaHCO}_3-\text{P}_o$ ) and moderately labile P ( $\text{NaOH}-\text{P}_i$  and  $\text{NaOH}-\text{P}_o$ ) fractions. However, in this case only  $\text{H}_2\text{O}-\text{P}_i$  was significantly ( $P < 0.05$ ) higher in TSP than MPR treated soil.

Minjingu PR was more effective than TSP in increasing acid extractable P ( $\text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2-\text{P} + \text{HCl}-\text{P}_i$ ). Though not statistically different, acid extractable P ( $\text{HCl}-\text{P}_i$ ) in MPR ( $144.8 \text{ mg P kg}^{-1}$  soil) treated soil was twice that in TSP ( $69.7 \text{ mg P kg}^{-1}$  soil) treated soil. This suggests that some of the P applied as MPR remained in the soil as originally applied apatite as previously discussed under Sasanda soil. The  $\text{HCl}-\text{P}_i$  in the MPR treated soil was thought to be due to undissolved PR. On the other hand,  $\text{HCl}-\text{P}_i$  from TSP treated soil probably resulted from conversion of soluble P to very slowly soluble P.

The results of  $\text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2$  extractable P were  $110.6$  and  $12.5 \text{ mg P kg}^{-1}$  soil for MPR and TSP treated soils, respectively. These suggest that MPR may contain some fraction of P that was not extractable with HCl, thus contributing to residual P ( $\text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2-\text{P}$ ). It is also important to note that for MPR and TSP treated soils, the summation of  $\text{HCl}-\text{P}_i + \text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2-\text{P}$  were  $255.4 \text{ mg P kg}^{-1}$  and  $82.2 \text{ mg P}$

kg<sup>-1</sup>, respectively. Like in Sasanda, a substantial amount of the applied P (180 mg P kg<sup>-1</sup>) as either MPR or TSP over the three years' period did not dissolve. Moreover, it is important to note that the value (255.4 mg P kg<sup>-1</sup>) from MPR treated soil is above the amount (180 mg P kg<sup>-1</sup>) applied for three seasons. The 180 mg P kg<sup>-1</sup> soil assumed 15 cm depth plough layer. However, Suluti soil is very hard to cultivated and it is possible that the fertilizer materials was not incorporated uniformly within 15 cm depth, thus leading to high values of P in Suluti soil.

Similar explanations for non significant difference between MPR and TSP treated soils in Sasanda are applicable here. In this case increase in extractable P values was observed in all organically bound P fractions. This result is in agreement with Beck and Sanchez (1994) who found increased P<sub>o</sub> after a few months of inorganic P fertilization in Oxisols.

In Nkundi soil, MPR had relatively higher influence than TSP on labile (H<sub>2</sub>O-P<sub>i</sub> and NaHCO<sub>3</sub>-P<sub>i</sub>) and moderately labile P (NaOH-P<sub>i</sub> and NaOH-P<sub>o</sub>) fractions, but only NaOH-P<sub>i</sub> and H<sub>2</sub>O-P<sub>i</sub> were significantly (P<0.05) higher in MPR than TSP treated soil. This indicates higher solubility of MPR in this soil, which suggests that most of the MPR applied, was available for plant uptake. Before the first season, the soil pH was 5.9 in the top 8 cm and 5.3 below 8 cm and exchangeable Ca was 0.2 cmol(+) kg<sup>-1</sup>. Soil was sampled within 15 cm depth. High dissolution of the MPR may be related to the low pH of this soil. After three years of cultivation, pH in MPR treated soil was lowered from 5.5 (in the control) to 5.1; which may indicate more favourable condition for MPR dissolution in this soil. Furthermore, this soil had low

fixing capacity hence relatively high proportion of P released from TSP remained in available forms.

The result showed that, extractable HCl-P<sub>i</sub> from TSP treated soil was significantly ( $P < 0.05$ ) higher than that extracted from MPR. In contrast, Mutuo *et al* (1999) reported that HCl-P<sub>i</sub> fraction remained relatively constant following TSP application, and it contained 24 to 32% of the P applied as PR. In this study, the change in extractable P was 39.9 and 3.1% for TSP and MPR, respectively. The results indicate that most of the TSP applied was converted to Ca-P, probably due to relatively high exchangeable Ca of 2.1 cmol (+) kg<sup>-1</sup> within the 8 cm depth. The actual proportion of the P remaining in an available form will depend upon contact with the soil, time for reaction and other factors (Brady, 1990).

The study shows that the effect of TSP and MPR on most of the P fractions was non significant. Triple super phosphate and MPR showed non-significant differences on organically bound fractions and NaHCO<sub>3</sub>-P<sub>i</sub> in all soils. The result was probably due to high variability of fractionation results. Organic phosphorus (P<sub>o</sub>) was determined by the difference between P<sub>t</sub> and P<sub>i</sub> for a given extract, and there are multiple sources of error (Buehler *et al.*, 2002) associated with this approach. Magid and Nielsen (1992) reported high variability due to repeated measurement of NaHCO<sub>3</sub>-P<sub>o</sub> and NaOH-P<sub>o</sub>. Tiessen and Moir (1993) proposed the possibility of P<sub>i</sub> precipitation along with organic matter upon acidification and erroneously being determined as P<sub>o</sub> (P<sub>t</sub>-P<sub>i</sub>). On the other hand, P<sub>o</sub> compounds could be hydrolyzed in

acidic solution during the colorimetric measurement of  $P_i$  (Condrón *et al.*, 1990; Gerke and Jungk, 1991).

Slightly higher increases in labile and moderately labile P values in TSP than MPR treatments from both Sasanda and Suluti were possibly due to high dissolution of TSP as opposed to the MPR. In addition, the two soils differed in P fixation capacity. Sasanda had very high and Suluti having moderate P fixing capacity, thus readily soluble P was prone to fixation in these soils. Nkundi soil behaved differently. There were slightly greater increases in labile and moderately labile P in MPR than TSP treatments. Low pH of 5.3 within 15 cm depth might have influenced MPR dissolution in this soil, resulting in more easily extractable P as also reported by Khasawneh and Doll (1978). Furthermore, it is possible that TSP released P rapidly to readily available form compared to MPR which released P slowly with time; consequently P release from TSP exceeded plant uptake and led to more P fixation. The surface soil of Sasanda has higher aluminium saturation (11%) than Nkundi soil (3%) (Szilas, 2002) which was likely to cause higher P fixation in Sasanda soil than in Nkundi soil. Purnomo and Black (1994) using PR as P source observed that, high  $Al^{3+}$  saturation of 15% caused relatively high PR solubility as well as high fixation while low  $Al^{3+}$  saturation of 3% caused relatively low PR dissolution and P fixation, leaving relatively high levels of available P. Therefore, high aluminium saturation, might be the best explanation of more NaOH- $P_i$  observed in Sasanda soil than other soils.

Total P increase following three years of MPR and TSP application in Suluti soil (370.1 and 365 mg P kg<sup>-1</sup> for TSP and MPR, respectively) suggests that the P applied was not incorporated uniformly to a depth of 15 cm. However, the total amount of P that was applied to this soil in three consecutive years of cultivation and fertilization was 180 mg P kg<sup>-1</sup> hence this suggests anomaly. Therefore, the fertilizer was probably incorporated within a depth of 7.5 cm.

Likewise, the same amount of fertilizer was applied in Sasanda and Nkundi soils. However, increase in extractable P in Sasanda was 290.2 and 198.6 mg P kg<sup>-1</sup> for TSP and MPR treatments, respectively while it was 207.1 and 200.8 mg P kg<sup>-1</sup> for TSP and MPR treatments, respectively in Nkundi soil.

Results further indicate that plants in suluti and Nkundi took relatively higher amount of P from the fertilizer materials soils than in Sasanda, probably due higher P fixation in the later. These results further reveal that in Sasanda soil, plants absorbed more P from MPR than TSP treated soil. This was probably because the water-soluble P source was more susceptible to fixation by Al and Fe, thus decreasing very easily in soil than sparingly soluble MPR. Rapid release and slow release of P from TSP and MPR, respectively was the main reason for higher fixation in the TSP treatment. This argument is supported by amount of undissolved MPR (42.2 mg P kg<sup>-1</sup> as HCl-P<sub>i</sub>) which could supply P even after three years of cultivation while for TSP only trace amounts of P remained in undissolved (5.4% mg P kg<sup>-1</sup> as HCl-P<sub>i</sub>) form.

#### **4.4 Pot experiment**

##### **4.4.1 Visual observation of maize growth**

Seven days after sowing (DAS) all pots had the pre germinated seeds completely sprouted. In the fourth week after planting, maize plants in the treatment control of Sasanda and Nkundi soils had weak, thin and stunted plants. Other symptoms observed were dying of lower leaves, purplish coloration of maize stem and leaf margins. These symptoms indicated severe P deficiency and probably N deficiency in the three soils. This observation suggested that these soils were deficient in those nutrients. On the other hand, maize plants in P treatment control (which received adequate levels of N, K, Zn but no P) in Suluti soil were slightly greenish suggesting that P and N were not as deficient as in Sasanda and Nkundi.

Maize grown on both residual TSP and MPR in Suluti and Nkundi soils had vigorous growth with strong stems and greenish leaves. However, plants grown in Sasanda soil were stunted with thin stems and purplish coloration on maize stems, yellowish leaves and premature death of lower leaves. These observations indicate that in Sasanda, residual P from either TSP or MPR did not supply sufficient P to alleviate P deficiency in the soil. These observations suggest that, the P fertilizer applied in Sasanda soil during the previous three seasons has been converted to forms unavailable for plant uptake. Szilas (2002) reported that of the three soils under study, Sasanda had higher P fixing capacity than Suluti while Nkundi had much lower P fixing capacity.

Low rates of fresh P application of TSP resulted in stunted plants with purplish coloration on maize stems, except in Nkundi soil. Where MPR was applied at the low rate, plants had purplish coloration on stems and were relatively more stunted as compared with TSP treatment. High rates of fresh P application gave strong plants with vigorous growth in all soils, except Sasanda when MPR was used as a source of P. In MPR treatments, plants had purplish coloration on stems and were relatively stunted. Therefore, in Sasanda soil fresh application of MPR did not supply P to sufficiency level even at the  $180 \text{ mg P kg}^{-1}$  application rate. These results imply that neither residual nor high fresh application of MPR supplied sufficient level of P for plant uptake in Sasanda. These results indicate the need for maintenance application of P where phosphate fertilizers have been applied for three seasons, and that higher rates of MPR should be tested to establish the optimum rate of application.

#### **4.4.2 Effects of P sources on dry matter yield**

The data on dry matter yield at 42 days after sowing (DAS) are presented in Table 5. The dry matter yield (DMY) of the control treatments ranged from 2.07 g/pot in Sasanda soil to 23.04 g/pot in Suluti soil. This indicates that the three soils varied in productivity and that Suluti was more productive than the other two soils.

**Table 5. Effects of P sources on dry matter yield at 42 DAS in three soils**

Treatments (mg kg <sup>-1</sup> soil)	Dry matter yield (g/pot) in soils		
	Sasanda	Suluti	Nkundi
P <sub>0</sub> N <sub>0</sub> K <sub>0</sub> Zn <sub>0</sub>	2.7 <sup>c</sup>	7.0 <sup>c</sup>	9.2 <sup>c</sup>
P <sub>0</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub>	2.1 <sup>c</sup>	23.0 <sup>d</sup>	9.2 <sup>c</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Residual TSP)	16.1 <sup>d</sup>	31.9 <sup>b</sup>	35.6 <sup>cd</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Residual MPR)	19.2 <sup>d</sup>	33.9 <sup>ab</sup>	38.6 <sup>bcd</sup>
P <sub>60</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh TSP)	23.7 <sup>cd</sup>	32.7 <sup>b</sup>	39.2 <sup>bc</sup>
P <sub>60</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh MPR)	27.9 <sup>bc</sup>	27.8 <sup>c</sup>	34.1 <sup>d</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh TSP)	39.2 <sup>a</sup>	37.1 <sup>a</sup>	44.5 <sup>a</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh MPR)	34.7 <sup>ab</sup>	32.9 <sup>b</sup>	41.9 <sup>ab</sup>
CV%	21.3	7.3	8.4

Means in the same column followed by the same letter(s) are not significantly different according to Duncan Multiple range Test at 0.05 level of significance.

In all soils, both residual and freshly applied P significantly ( $P \leq 0.05$ ) increased DMY over the P control treatment. These results suggest that P was a limiting nutrient in these soils. This observation is in agreement with the  $P_i$  results in Table 3 (0.4, 7.4, and 2.1 mg P kg<sup>-1</sup> for Sasanda, Suluti and Nkundi, respectively) which indicated that the three soils had deficient levels of P. However, this study revealed that although not at sufficiency level, Suluti had higher potential to supply plant available P from native P than other soils, a result which is also supported by its high FeO- $P_i$  value. Therefore, P application from external sources is essential for attaining and maintaining high productivity.

In Sasanda soil, high rates (180 mg P kg<sup>-1</sup>) of freshly applied P either as TSP or MPR, gave significantly higher DMY over residual P from the two sources. Significant increase ( $P \leq 0.05$ ) in DMY over the residual P was also obtained with the low rate (60 mg P kg<sup>-1</sup>) of MPR while DMY from the low TSP rate was not significantly different to that from the residual sources. This indicates that fresh low application rates maintained a higher level of readily available P than that from residual TSP because of greater fixation from the latter case. Probably, most of the P from residual TSP was already in forms unavailable to plant uptake. Phosphorus fractionation data (Appendix 2) indicate that 67.6% of the P recovered from TSP treated soils was extracted as moderately labile (NaOH- $P_i$ ). Minjingu PR showed a similar trend as TSP.

In addition when TSP was used as a P source, DMY increased with increase in application rate while fresh applications of MPR showed only slight increases in

yield with increased in application rates. The probable reason for this observation was that, most of the P applied as TSP was rapidly fixed before plants took it. This was probably because readily soluble P sources like TSP supplied more plant available P than MPR, which usually becomes available with time.

In Suluti soil, low freshly applied TSP and residual TSP had comparable DMY which were significantly lower than high application rate of TSP. However for MPR, low fresh application rate gave significantly lower DMY than residual MPR. The higher application rate of MPR, had slightly lower DMY than residual MPR. Lower performance of freshly applied MPR may be due to the relatively higher P and higher pH in this soil than the other soils. Freshly applied TSP had significantly higher DMY than their respective freshly applied. High response of maize plant following TSP application compared to residual TSP and fresh MPR may be due to rapid release of P from TSP as discussed in section 4.3. Dry matter yield increased with application rates for the two P sources.

In Nkundi, residual P from MPR treated soil had slightly higher DMY than both residual TSP and low freshly applied P as MPR. High application rate of P applied as MPR led to only slight higher DMY than the residual MPR source. These observations were probably due to high readily available ( $\text{H}_2\text{O-P}_i + \text{NaHCO}_3\text{-P}_i = 75.8 \text{ mg P kg}^{-1}$ ) P that remained in the soil after three years of MPR application and cropping (Table 4). On the other hand for the TSP, freshly applied P at lower rate slightly increased DMY over residual TSP. However, both had significantly

lower DMY than that for the high rate of freshly applied TSP. It is important to note that, like in Sasanda soil DMY increased with increase in application rate.

The DMY from both residual MPR (38.6, 33.9 and 19.2 g/pot for Nkundi, Suluti and Sasanda, respectively) and TSP (35.6, 31.9 and 16.1 g/pot for Nkundi, Suluti and Sasanda, respectively) were highest in Nkundi followed by Suluti. This trend is consistent with increase in readily available P ( $\text{H}_2\text{O-P}_i + \text{NaHCO}_3\text{-P}_i$ ) which was 75.8, 57.2 and 21.0 mg P  $\text{kg}^{-1}$  for Nkundi, Suluti and Sasanda, respectively (Table 4). It is also in agreement with the trend of FeO- $\text{P}_i$  results reported in Table 3 and Appendix 1, and the standard P requirement as discussed in section 4.2. Moreover, the P fractionation results revealed that most of the P (67.6 and 55.7% from TSP and MPR, respectively) in Sasanda soil remained in the moderately available pool (NaOH-  $\text{P}_i$ ).

The trend of phosphorus fractionation and FeO- $\text{P}_i$  data pose some contradiction, which lead to interpretation problems. Despite relatively high levels of labile P ( $\text{H}_2\text{O-P}_i$ ,  $\text{NaHCO}_3\text{-P}_i$  and FeO- $\text{P}_i$ ) and moderately labile P (NaOH- $\text{P}_i$ ) in TSP than MPR treated soil at Sasanda and Suluti, slightly higher DMY was observed in MPR than TSP treatments. Moreover, Nkundi had higher labile P in MPR than TSP treated soil while the FeO- $\text{P}_i$  data indicated higher values in TSP than MPR treated soil. There is a possibility that P that diffused into soil aggregates was not released into the soil solution. This might have resulted in low extractable P especially from very high fixing soils (2430 mg P  $\text{kg}^{-1}$ ) of Sasanda and medium fixing soils (209 mg P  $\text{kg}^{-1}$ ) of Suluti compared to Nkundi (181 mg P  $\text{kg}^{-1}$ ). Linquist *et al.*, (1997)

reported that most soil tests and P fractionation procedures measure all labile P because soil aggregates are destroyed.

#### **4.4.3 Relative agronomic effectiveness (RAE) of MPR treatments**

The relative agronomic effectiveness data are presented in Table 6. The mean relative agronomic effectiveness of MPR based on dry matter yield ranged from 88.0-122.0, 49.4-122.1 and 82.8-111.2% for Sasanda, Suluti and Nkundi, respectively. RAE values from residual P sources in Nkundi were lower than both Sasanda and Suluti soil, which had comparable values. This was thought to be due to lower fixation of P from readily soluble TSP in Nkundi soil than that of Sasanda and Suluti soils.

However, the RAE of residual MPR from the three soils was above 100%, indicating higher residual effect of MPR than TSP. Higher residual effect of MPR on DMY than TSP was due to the fact that, TSP released P very fast which resulted in high fixation compared to MPR which released P slowly, hence high availability to plants.

**Table 6. Relative agronomic effectiveness of MPR for DMY in three soils**

Rates (mg kg <sup>-1</sup> soil) and P sources	Relative agronomic effectiveness (%)in three soils		
	Sasanda	Suluti	Nkundi
180 Residual TSP	100	100	100
60 Fresh TSP	100	100	100
180 Fresh TSP	100	100	100
180 Residual MPR	122.0	122.1	111.2
60 Fresh MPR	119.1	49.4	82.8
180 Fresh MPR	88.0	70.3	92.7

In Sasanda soil, the rate of 60 mg P kg<sup>-1</sup> as MPR had higher RAE value than the rate of 180 mg kg<sup>-1</sup>. In the other two soils, the low application rate had lower RAE values than the higher rates. These differences are thought to be due to higher fixation of P from TSP in Sasanda soil compared to the other soils, leading to lower performance of TSP than MPR in this soil. Suluti soil had the lowest RAE at low rate of freshly applied MPR compared to the other two soils. The lowest RAE value of MPR in Suluti soil indicate low effectiveness of freshly applied MPR in Suluti soil which was probably due to high labile native P coupled with relatively high pH in this soil (Appendix 1 and Table 2). These properties might have caused low MPR dissolution leading to low P release from MPR.

#### **4.4.4 Effects of P sources and application rate on P concentration and uptake**

The results for P concentration in plants as influenced by P sources are presented in Table 6. Phosphorus concentration in plant ranged from 0.06-0.18, 0.09-0.3, 0.06-0.26% for Sasanda, Suluti and Nkundi soils, respectively. All the treatments significantly ( $P \leq 0.05$ ) increased P concentration in maize shoots over the treatment control. According to Jones and Eck (1973) sufficient P range for maize seedlings (35-45 days) is 0.25-0.40%. Therefore, based on this criterion, P concentration values in plants grown in Sasanda soil were below sufficient levels while other soils had values that ranged from deficient to marginally sufficient levels.

In Sasanda soil, all residual P sources gave shoot P concentration comparable to those of fresh MPR applications while P from fresh TSP application gave significantly lower shoot P concentration. The P concentration in the maize shoots following TSP application was significantly lower than that from residual P sources. This was probably because of the rapid fixation of P released from TSP application. This argument is supported by DMY and P uptake which increased significantly with increasing application rates when P was applied as fresh TSP while P concentration in plant shoots was maintained at 0.09%.

**Table 7. Effects of P sources on P uptake and concentration in plant shoots after 42 days of growth under glasshouse conditions.**

Treatments (mg P kg <sup>-1</sup> soil)	Phosphorus concentration (%) and uptake (mg/pot)					
	Sasanda		Suluti		Nkundi	
	P (%)	P mg/pot	P (%)	P mg/pot	P (%)	P mg/pot
P <sub>0</sub> N <sub>0</sub> K <sub>0</sub> Zn <sub>0</sub>	0.06 <sup>c</sup>	1.6 <sup>c</sup>	0.09 <sup>c</sup>	6.5 <sup>l</sup>	0.06 <sup>c</sup>	5.7 <sup>d</sup>
P <sub>0</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub>	0.07 <sup>c</sup>	1.3 <sup>c</sup>	0.12 <sup>c</sup>	27.3 <sup>c</sup>	0.09 <sup>dc</sup>	8.5 <sup>d</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Residual TSP)	0.16 <sup>a</sup>	27.2 <sup>d</sup>	0.20 <sup>b</sup>	63.0 <sup>cd</sup>	0.15 <sup>c</sup>	53.2 <sup>c</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Residual MPR)	0.18 <sup>a</sup>	33.2 <sup>cd</sup>	0.22 <sup>b</sup>	73.6 <sup>bc</sup>	0.14 <sup>c</sup>	55.4 <sup>c</sup>
P <sub>60</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh TSP)	0.09 <sup>b</sup>	21.8 <sup>d</sup>	0.20 <sup>b</sup>	65.3 <sup>cd</sup>	0.17 <sup>bc</sup>	65.3 <sup>c</sup>
P <sub>60</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh MPR)	0.17 <sup>a</sup>	47.5 <sup>b</sup>	0.18 <sup>b</sup>	51.2 <sup>d</sup>	0.16 <sup>c</sup>	53.7 <sup>c</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh TSP)	0.09 <sup>b</sup>	36.9 <sup>bc</sup>	0.30 <sup>a</sup>	111.4 <sup>a</sup>	0.26 <sup>a</sup>	113.6 <sup>a</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh MPR)	0.18 <sup>a</sup>	61.0 <sup>a</sup>	0.28 <sup>a</sup>	90.8 <sup>b</sup>	0.21 <sup>ab</sup>	86.2 <sup>b</sup>
CV%	12.4	24.5	14.0	16.2	15.3	17.7

Means in the same column followed by the same letter(s) are not significantly different according to Duncan Multiple range Test at 0.05 level of significance.

On the other hand, MPR gave comparable P concentration from residual and fresh P sources. Likewise P uptake increased with application rates and fresh P applied at a rate of 180 mg P kg<sup>-1</sup> had significantly higher P uptake than residual P.

Residual MPR gave P uptake which was slightly higher than those from the residual TSP treatment. However, freshly applied P showed significantly higher P uptake from MPR than TSP treatments which might be due to greater fixation of available P from TSP than from MPR in Sasanda soil. Triple super phosphate which is water-soluble increased the concentration of soluble P in soil which was susceptible to fixation (by Al and Fe), and subsequently maintained a low equilibrium concentration of soluble P. It is also possible that initially plants took a large amount of P but after a few days the plants depended on previously absorbed P leading to dilution and hence low P concentration in plants.

In Suluti soil, both residual and fresh low application of MPR and TSP gave comparable P concentrations in plant shoots. The P concentration was below sufficiency range reported by Jones and Eck (1973), suggesting that higher application for fresh and maintenance application for residual treatments are required. Indeed the high application rate of either TSP or MPR gave significantly higher P concentrations in shoots than low applications, and the former P concentrations were within the sufficiency range reported by Jones and Eck (1973). Likewise, the P uptake increased significantly as P application rate was increased. Triple superphosphate had significantly higher influence on P uptake when P was applied at high application rate than at low application rate and TSP had slightly

higher influence on P uptake than MPR. Phosphorus uptake from the residual MPR was significantly higher than that obtained from a fresh application of MPR at 60 mg kg<sup>-1</sup> soil.

In Nkundi soil, residual effects of MPR and TSP as well as low rates of fresh applications of the two P sources gave comparable P concentrations which were below the sufficiency level. However, increase in P rate from both sources increased P concentration significantly. The high rate of P applied as TSP increased P concentration to sufficiency level whereas the same rate of P applied as MPR resulted in a P concentration that was slightly lower than the sufficiency level reported by Jones and Eck (1973). In all fresh P application rates, TSP gave slightly higher P concentration in maize shoots than MPR. In addition, the high application rate of 180 mg kg<sup>-1</sup> soil gave significantly higher uptake in TSP than MPR treatment. These observations indicate that MPR supplied relatively less P than TSP during the duration of the experiment. This is most likely due to the slow release of P from MPR.

Phosphorus concentration values achieved with the high rates of P in Suluti and Nkundi soils (TSP fresh application) were within the sufficient range of 0.25-0.4% reported by Jones and Eck (1973). In addition, in Suluti and Nkundi soils, P uptakes from these treatments were comparable. The low P concentrations in maize shoots observed in Sasanda soil indicate that higher rates of P are required in Sasanda to achieve sufficient levels in plants. This is attributed to the low initial available P and high P fixing capacity of Sasanda soil. Sasanda soil had very low level of inorganic

P as determined by FeO-P<sub>i</sub> method (Appendix 2) and has high P fixing capacity. Szilas (2002) reported that the estimates of the amounts of initial P present in the soil indicated that Sasanda was extremely deficient in P compared to the other soils, used in this study. In addition Sasanda soil is known to have very high P requirement as explained in section 4.3.2.

These results indicate that three years of continuous application of P either as TSP or MPR did not build up sufficient residual P to eliminate the need for continued P application in the three soils differing widely in P fixation capacity. Therefore, maintenance application of P should be calibrated for these soils so as to increase their productivity and avoid unnecessary cost which may result from application of large amount of fertilizer.

#### **4.4.5 Effects of P sources and application rate on Ca uptake and concentration.**

The results for Ca concentration in plants as influenced by P sources and rate of application are presented in Table 8. Calcium concentration in plants ranged from 0.21-0.31, 0.23-0.33, 0.17-0.25% for Sasanda, Suluti and Nkundi soils, respectively. According to Jones and Eck (1973) the critical level of Ca in plants range 0.21-1.00%. Therefore, all treatments had sufficient levels of Ca in plant shoots. This sufficiency level of Ca in plant shoots however, may also be related to increase uptake of Ca to compensate for the reduced K uptake. It is known that deficiency K<sup>+</sup> in plant vacuoles is associated with increased uptake of Ca<sup>2+</sup> and Mg<sup>2+</sup> cations (Marschner, 1990).

**Table 8. Effects of P sources and application rate on Ca uptake and concentration in plant shoots after 42 days of growth under glasshouse conditions.**

Treatments (mg P kg <sup>-1</sup> soil)	Calcium concentration (%) and uptake (mg/pot)					
	Sasanda		Suluti		Nkundi	
	Ca (%)	Ca mg/pot	Ca (%)	Ca mg/pot	Ca (%)	Ca mg/pot
P <sub>0</sub> N <sub>0</sub> K <sub>0</sub> Zn <sub>0</sub>	0.29 <sup>ab</sup>	8.1 <sup>d</sup>	0.23 <sup>c</sup>	16.4 <sup>e</sup>	0.17 <sup>b</sup>	15.3 <sup>c</sup>
P <sub>0</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub>	0.31 <sup>a</sup>	6.2 <sup>d</sup>	0.28 <sup>abc</sup>	67.2 <sup>d</sup>	0.23 <sup>ab</sup>	20.1 <sup>c</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Residual TSP)	0.26 <sup>abc</sup>	43.3 <sup>c</sup>	0.25 <sup>bc</sup>	80.6 <sup>cd</sup>	0.25 <sup>a</sup>	87.5 <sup>ab</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Residual MPR)	0.30 <sup>ab</sup>	58.2 <sup>c</sup>	0.33 <sup>a</sup>	110.5 <sup>a</sup>	0.22 <sup>ab</sup>	85.5 <sup>ab</sup>
P <sub>60</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh TSP)	0.23 <sup>c</sup>	55.8 <sup>c</sup>	0.30 <sup>ab</sup>	97.4 <sup>abc</sup>	0.21 <sup>ab</sup>	82.9 <sup>ab</sup>
P <sub>60</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh MPR)	0.24 <sup>bc</sup>	67.2 <sup>bc</sup>	0.31 <sup>a</sup>	87.2 <sup>bcd</sup>	0.21 <sup>ab</sup>	72.5 <sup>b</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh TSP)	0.21 <sup>c</sup>	83.5 <sup>ab</sup>	0.30 <sup>ab</sup>	109.9 <sup>a</sup>	0.22 <sup>ab</sup>	96.9 <sup>a</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh MPR)	0.27 <sup>abc</sup>	92.7 <sup>a</sup>	0.32 <sup>a</sup>	105.9 <sup>ab</sup>	0.24 <sup>a</sup>	97.5 <sup>a</sup>
CV%	8.86	26.2	10.2	13.8	14.6	13.8

Means in the same column followed by the same letter(s) are not significantly different according to Duncan Multiple range Test at 0.05 level of significance.

In Sasanda soil, the treatment control had slightly higher Ca concentration than the P treatments. This was possibly due to dilution effect caused by improved plant growth as a result of alleviating P deficiency. This argument is supported by the P uptake data which show significantly higher values of Ca in the P treatments. Kadoghola (2001) and Marschner (1990) reported similar observations. Residual and fresh MPR gave slightly higher Ca concentration in plant than TSP in this soil. This may be due to high Ca (33.1%) in MPR (Harris, 1981). Calcium concentration slightly decreased with TSP application probably due to a dilution effect as a result of a sharp increase in plant growth at the high rate of TSP which may be supported by their respective plant uptake. Calcium uptake increased significantly with P application rate, but still MPR had slightly higher influence on Ca uptake than TSP at high application rate. These results indicated that P sources and especially MPR contributed appreciably to Ca supply.

In Suluti soil, there was slightly higher Ca concentration in MPR than TSP treated soils for both residual P and fresh P applications. In contrast, Ca uptake was slightly higher from TSP than MPR for fresh applications and significantly higher Ca uptake from the residual MPR than TSP. The high Ca uptake observed from freshly applied TSP was a result of increase in plant growth due to phosphorus supply, which suggest that TSP released more P which might have influenced high root development, hence high Ca uptake.

In Nkundi soil, slightly higher Ca concentration from MPR than TSP treated soil was observed at the high application rate, while low application rates gave

comparable values. The low and high rates of P applied as TSP, resulted in comparable Ca concentration, but Ca uptake increased slightly with the application rate. However, for MPR, uptake increased significantly with application rate despite the fact that there was only a slight increase in Ca concentration in shoots. These observations indicate that MPR has high potential for Ca supply to plants and that P sources improved Ca nutrition in these soils and that MPR had high potential for Ca release in these soils than TSP.

#### **4.4.6 Effects of P sources and application rate on K uptake and concentration**

The results for K concentration in plants as influenced by P sources and rates after 42 days of growth are presented in Table 9. Potassium concentration in plants ranged from 1.30-2.22, 0.81-1.48, 0.67-1.89 % for Sasanda, Suluti and Nkundi soils, respectively. Although 50 mg K kg<sup>-1</sup> was added to alleviate K deficiency, the K concentration in plants did not reach the sufficiency level in plant shoot proposed by Tandon (1995). Tandon (1995) proposed the sufficiency range of K in plant shoots to be 2.5-4.0%. These results showed that, all the soils did not supply K to sufficient level.

In Sasanda and Suluti soils, residual P from MPR gave slightly higher shoot K concentration than TSP. Potassium uptake was slightly higher with MPR than TSP in all soils. Likewise when P was applied at high rate in Sasanda soil, K concentration in plant shoots was significantly higher in MPR than TSP treated soil.

**Table 9. Effects of P sources on K uptake and concentration in plant shoots after 42 days of growth under glasshouse conditions**

Treatments (mg P kg <sup>-1</sup> soil)	Potassium concentration (%) and uptake (mg/pot)					
	Sasanda		Suluti		Nkundi	
	K (%)	K mg/pot	K (%)	K mg/pot	K (%)	K mg/pot
P <sub>0</sub> N <sub>0</sub> K <sub>0</sub> Zn <sub>0</sub>	2.22 <sup>a</sup>	60.9 <sup>d</sup>	1.48 <sup>a</sup>	103.0 <sup>c</sup>	1.88 <sup>a</sup>	165.4 <sup>c</sup>
P <sub>0</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub>	2.14 <sup>a</sup>	44.5 <sup>d</sup>	1.03 <sup>bc</sup>	237.7 <sup>cd</sup>	1.89 <sup>a</sup>	178.2 <sup>c</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Residual TSP)	1.94 <sup>ab</sup>	321.5 <sup>c</sup>	1.08 <sup>b</sup>	341.2 <sup>ab</sup>	0.95 <sup>b</sup>	339.1 <sup>ab</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Residual MPR)	2.13 <sup>a</sup>	398.3 <sup>abc</sup>	1.11 <sup>bc</sup>	377.4 <sup>a</sup>	1.02 <sup>b</sup>	391.2 <sup>a</sup>
P <sub>60</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh TSP)	1.66 <sup>bc</sup>	391.5 <sup>bc</sup>	0.83 <sup>cd</sup>	272.0 <sup>bcd</sup>	0.91 <sup>b</sup>	355.7 <sup>ab</sup>
P <sub>60</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh MPR)	1.72 <sup>bc</sup>	478.3 <sup>ab</sup>	0.82 <sup>cd</sup>	228.6 <sup>d</sup>	0.88 <sup>b</sup>	301.2 <sup>ab</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh TSP)	1.30 <sup>d</sup>	508.7 <sup>ab</sup>	0.83 <sup>cd</sup>	308.0 <sup>abc</sup>	0.68 <sup>b</sup>	303.3 <sup>ab</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh MPR)	1.60 <sup>c</sup>	554.6 <sup>a</sup>	0.81 <sup>d</sup>	264.9 <sup>bcd</sup>	0.67 <sup>b</sup>	276.3 <sup>b</sup>
CV%	9.2	24.0	11.4	15.5	17.5	16.6

Means in the same column followed by the same letter(s) are not significantly different according to Duncan Multiple range Test at 0.05 level of significance.

The high K content in the MPR treatment may be due to some K supplied by MPR. Harris (1981) reported that MPR contains 1.4% K<sub>2</sub>O. Potassium uptake in Sasanda soil followed similar trends, but the K uptake increased slightly in MPR than TSP treated soil, and so with different application rate. In Suluti soil, fresh applications from both sources caused slight to significant decreases in plant K concentration which led to deficient levels. Similarly, K concentration in plants grown in Nkundi soil treated with either TSP or MPR decreased significantly to severe deficient level. In both soils the decrease in K concentration in plants was greater at high rates of fresh P application than at low rates. Potassium uptake at low and high P application rates was slightly higher in TSP than in MPR treatment. These observations were probably due to negative interaction between Ca and K. The results showed that there were lower K concentration values in P treatments than in P treatment control. Both of the P sources supplied Ca in addition to P and it is thought that the improvement in Ca supply might have depressed K uptake. Sasanda soil had higher content of K than Nkundi and Suluti soils, thus plants grown in Sasanda soil had relatively high K concentration in plant shoots.

In fact both P sources decreased K concentration in plant at high application rates. This indicates that high P application rates resulted in an imbalance of K when it is present at deficient level, thus K should be calibrated along with P application rates.

#### **4.4.7 Effects of P sources and application rate on Mg uptake and concentration**

The concentration of Mg as influenced by P sources and application rates are shown in Table 10. The Mg concentration ranged from 0.13-0.20, 0.10-0.22 and 0.13-0.24% for Sasanda, Suluti and Nkundi soils, respectively. According to Tandon (1995), the sufficient level of Mg in plant shoot ranges between 0.15-0.45%. Therefore, from this study Mg levels in Nkundi ranged from deficient to sufficient level while in Sasanda and Suluti it was marginal to sufficient. This observation was probably caused by enhanced uptake of Mg, as a compensation for the reduced K uptake.

In Sasanda, P resulted in a slight decrease in Mg concentrations probably to compensate the increased K uptake. However, the concentration of Mg in plants ranged from marginal to adequate levels. In both Nkundi and Suluti soils fresh applications of both P sources resulted in sufficient levels of K in plant shoots. However, residual P from TSP was associated with a sufficient level of Mg in plant shoot in Nkundi soil but a deficient level of Mg in Suluti soil. Minjingu PR gave Mg concentrations close to the sufficiency level in the two soils.

In Suluti, fresh applications of P from both sources resulted in significant increases in Mg concentration in plant shoots. These treatments had low concentration of K in plants. Therefore, these results may be due to an interaction between Mg and K.

**Table 10. Effects of P sources on Mg uptake and concentration in plant shoots after 42 days of growth under glasshouse conditions**

Treatments (mg P kg <sup>-1</sup> soil)	Magnesium concentration (%) and uptake (mg/pot)					
	Sasanda		Suluti		Nkundi	
	Mg (%)	Mg mg/pot	Mg (%)	Mg mg/pot	Mg (%)	Mg mg/kg
P <sub>0</sub> N <sub>0</sub> K <sub>0</sub> Zn <sub>0</sub>	0.18 <sup>a</sup>	4.9 <sup>e</sup>	0.12 <sup>de</sup>	8.2 <sup>g</sup>	0.16 <sup>bc</sup>	15.1 <sup>c</sup>
P <sub>0</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub>	0.20 <sup>a</sup>	4.0 <sup>e</sup>	0.16 <sup>bc</sup>	37.4 <sup>ef</sup>	0.22 <sup>ab</sup>	19.0 <sup>c</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Residual TSP)	0.13 <sup>a</sup>	22.4 <sup>d</sup>	0.10 <sup>c</sup>	31.0 <sup>f</sup>	0.15 <sup>c</sup>	55.3 <sup>b</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Residual MPR)	0.15 <sup>a</sup>	30.6 <sup>cd</sup>	0.14 <sup>cd</sup>	46.9 <sup>de</sup>	0.13 <sup>c</sup>	49.9 <sup>b</sup>
P <sub>60</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh TSP)	0.13 <sup>a</sup>	32.2 <sup>cd</sup>	0.19 <sup>ab</sup>	61.5 <sup>bc</sup>	0.16 <sup>bc</sup>	64.6 <sup>ab</sup>
P <sub>60</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh MPR)	0.14 <sup>a</sup>	38.7 <sup>bc</sup>	0.18 <sup>b</sup>	50.5 <sup>cd</sup>	0.18 <sup>bc</sup>	60.7 <sup>b</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh TSP)	0.13 <sup>a</sup>	50.2 <sup>ab</sup>	0.22 <sup>a</sup>	80.4 <sup>a</sup>	0.22 <sup>ab</sup>	97.4 <sup>a</sup>
P <sub>180</sub> N <sub>200</sub> K <sub>50</sub> Zn <sub>10</sub> (Fresh MPR)	0.16 <sup>a</sup>	57.3 <sup>a</sup>	0.22 <sup>a</sup>	72.1 <sup>ab</sup>	0.24 <sup>a</sup>	99.1 <sup>a</sup>
CV%	13.4	27.8	12.3	13.3	16.6	14.8

Means in the same column followed by the same letter(s) are not significantly different according to Duncan Multiple range Test at 0.05 level of significance.

On the other hand, higher Mg concentration and uptake in Nkundi than the other soils especially for the fresh applications, was probably due to relatively high Mg content in this soil. Magnesium levels were marginal in Sasanda and Suluti soil and although P application appear to increase Mg, this was attributed to an imbalance with K, thus if adequate K is supplied, the Mg supply should be optimized.

## CHAPTER FIVE

### 5.0 CONCLUSIONS AND RECOMMENDATIONS

#### 5.1 Conclusions

In view of the results reported in this study, it is concluded that:

1. The release and distribution of different P fractions is dependent on the P source and soil characteristics. Sasanda, which is a high P fixing soil, had most of its  $P_i$  in moderately labile (NaOH-  $P_i$ ) form while moderate to low fixing soils had more  $P_i$  in the readily labile ( $\text{NaHCO}_3$  -  $P_i$ ) fractions.
2. The results indicated that fractionation procedure was unable to detect precisely the available pool and some other mechanisms affected plant available P.
3. The results indicated that three years of continuous application of P either as TSP or MPR did not build up sufficient residual P to eliminate the need for continued application of P in three soils widely differing in P fixation capacity.
4. MPR gave higher residual effects on plant growth than TSP and this is attributed to high RAE which was above 100%.

5. Both P sources resulted in increased Ca uptake from three soils which had marginal Ca levels, but MPR had a higher effect than TSP. This means MPR is relatively better than TSP in improving Ca nutrition in soils.
6. Both P sources decreased K concentration in plant at high application rates. This indicates that high P application rates caused imbalance of K when present at marginal level. Thus K needs should be calibrated along with P application rates.

## 5.2 Recommendations

From these conclusions, the following recommendations were made:

1. For the soils that had seasonal phosphate fertilizer applications, maintenance P requirement should be calibrated under field condition so as to avoid depletion of nutrients.
2. Further research is needed to assess the relationship between P fractions and labile P forms ( $\text{H}_2\text{O-P}_i$  and  $\text{NaHCO}_3\text{-P}_i$  and  $\text{NaHCO}_3\text{-P}_o$ ).
3. Further research is needed to calibrate the optimum level of other nutrients that may affect crop performance where TSP or MPR have been applied.

4. This experiment should be continued using high rates of P in order to determine the time and rate of application that will lead to optimum levels of P in the soils.

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## APPENDICES

**Appendix 1. Sequentially and non-sequentially (FeO-P) extractable P fractions following application of either TSP or MPR at 120 kg/ha/season for three seasons.**

P Fractions	Extractable P (mg kg <sup>-1</sup> soil)								
	Sasanda			Suluti			Nkundi		
	Control	TSP	MPR	Control	TSP	MPR	Control	TSP	MPR
H <sub>2</sub> O-P <sub>i</sub>	3.1	10.0	6.4	5.2	36.1	17.9	5.2	25.8	35.5
NaHCO <sub>3</sub> -P <sub>i</sub>	17.1	47.6	34.8	25.0	131.8	69.6	36.0	54.5	81.5
NaHCO <sub>3</sub> -P <sub>o</sub>	10.8	39.3	11.1	16.7	31.2	29.6	5.0	26.0	18.4
NaOH-P <sub>i</sub>	116.8	312.9	227.4	68.8	140.8	105.5	40.8	57.8	73.5
NaOH-P <sub>o</sub>	108.8	131.8	62.8	49.8	113.5	52.6	18.8	41.3	64.4
HCl	26.4	31.8	68.6	33.0	102.6	177.7	22.6	105.2	28.8
H <sub>2</sub> SO <sub>4</sub> -P <sub>i</sub>	120.3	120.1	190.8	134.0	146.5	244.6	106.4	131.2	133.5
Total-P	403.3	693.5	601.9	332.5	702.6	697.5	234.7	441.8	435.6
NaHCO <sub>3</sub> -P <sub>t</sub>	27.9	86.9	45.9	41.7	163.1	99.2	41.0	80.5	99.9
NaOH-P <sub>t</sub>	225.6	444.7	290.2	118.6	254.3	158.1	59.6	99.1	135.9
FeO-P <sub>i</sub>	0.4	3.7	3.2	7.4	71.7	34.1	2.1	72.0	38.6

**Appendix 2. Recovery of P fertilizer by sequential P fractionation procedure following application of either TSP or MPR at 120 kg/ha/season for three seasons.**

P Fraction	Values expressed as percentage of total increased P in the soil					
	Sasanda		Suluti		Nkundi	
	TSP	MPR	TSP	MPR	TSP	MPR
H <sub>2</sub> O-P <sub>i</sub>	2.37	1.63	8.33	3.47	9.92	15.10
NaHCO <sub>3</sub> -P <sub>i</sub>	10.51	8.96	28.87	12.21	8.93	22.65
NaHCO <sub>3</sub> -P <sub>o</sub>	9.82	0.15	3.92	3.53	10.14	6.67
NaOH-P <sub>i</sub>	67.55	55.66	19.48	10.07	8.19	16.26
NaOH-P <sub>o</sub>	7.94	-23.13	17.20	0.75	10.87	22.70
HCl	1.85	21.24	18.82	39.66	39.94	3.11
H <sub>2</sub> SO <sub>4</sub> -P <sub>i</sub>	-0.04	35.48	3.38	30.30	12.01	13.51
Total-P	100	100	100	100	100	100
NaHCO <sub>3</sub> -P <sub>t</sub>	20.28	9.03	32.79	15.74	19.08	29.33
NaOH-P <sub>t</sub>	75.49	32.54	36.88	11.03	19.08	38.98