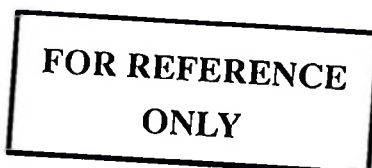


EFFECTS OF LIMESTONE, MINJINGU PHOSPHATE ROCK
AND GREEN MANURE APPLICATION ON IMPROVEMENT
OF ACID SOILS IN TONGA, BUTARE, RWANDA



BY

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ABSTRACT

A study was conducted under pot and field conditions to assess the effects of limestone, Minjingu Phosphate Rock (MPR) and green manures (GMs) on maize yield, soil properties and nutrient uptake. The treatments tested in the greenhouse experiment were four rates of limestone applied either alone or in combination with MPR and/or green manures. In the field experiment, 13 treatments were tested namely an absolute control, recommended rate of NPK and burned lime, NP and limestone, combinations of any two of the following materials: limestone, MPR, Tithonia GM, Tephrosia GM, and combinations of three of these amendments. Soil analysis at the beginning of the experiment revealed that the soil was deficient in N, P, and K, had low levels of Ca and Mg and toxic levels of exchangeable Al. Application of GMs improved the supply of N and K appreciably while limestone played a great role in reducing exchangeable Al. A significant contribution of P was from MPR. A combination of MPR, GMs and limestone supplied ample amounts of N, P, K, Ca, Mg and reduced exchangeable Al and hence resulted into high yield. However, high rates of limestone decreased DM yield and nutrient uptake in the treatment with three amendments. A significant increase in DM yield was obtained in pots, which received a combination of low rate of limestone (1/4 of the lime requirement), MPR and GMs. In general Tithonia application gave higher yields than Tephrosia. These results were consistent with the higher quality of Tithonia biomass relative to Tephrosia biomass. The green manures in combination with MPR increased P uptake significantly. Nutrient concentration data from both field and pot experiments indicated serious deficiencies of P, K and N consistent with soil analysis

data but Ca, Mg, Zn and Cu were in the sufficiency range. Furthermore, the results indicated that using a combination of moderate rates of limestone, MPR and GMs is the best strategy in improving acid soils in Tonga, Rwanda.

DECLARATION

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

Signature:.....

Date:.....

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DEDICATION

To my beloved wife Vestine Mukashema and children, R.N. Shema, C. N. Ishimwe and L.N. Hirwa merit special mentions for without this the completion of the work would have been extremely difficult. I also dedicate it to my late parents in law and late sister (T. Mukangarambe).

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LIST OF ABBREVIATIONS AND SYMBOLS

$\mu\text{g/pot}$	Micro-gram per pot
a.s.l.	Above sea level
Al	Aluminium
ANOVA	Analysis of Variance
C	Carbon
C:N	Carbon:nitrogen ratio
Ca	Calcium
CEC	Cation exchange capacity
cmol (+) kg^{-1}	Centimole cation per kilogram
CV	Coefficient of variation
DM	Dry matter
DMRT	Duncan's multiple range test
e.g.	example
<i>et al.</i>	and others
FAO	Food and Agriculture Organisation
GM	Green manure
H_2O_2	Hydrogen peroxide
H_2SO_4	Sulphuric acid
HNO_3	Nitric acid
i.e.	such as
K	Potassium
K_2O	Potassium oxide

KCl	Potassium chloride
Limest.	Limestone
Mg	Magnesium
MPR	Mijingu phosphate rock
N	Nitrogen
OC	Organic carbon
OH ⁻	Hydroxyl ion
P	Phosphorus
P ₂ O ₅	Phosphorus pentoxide
PR	Phosphate rock
SUA	Sokoine University of Agriculture
Tephr.	Tephrosia
Tith.	Tithonia
Vs	Versus

CHAPTER ONE

1.0 INTRODUCTION

Toxicity of aluminium (Al), iron (Fe), manganese (Mn) and hydrogen (H^+) and deficiencies of calcium (Ca), magnesium (Mg), potassium (K) and phosphorus (P) are the fundamental biophysical causes for the declining per capita food production in many parts of the world, especially in acid soils of sub-Saharan Africa (Jackson, 1967). In many acid soils ($pH < 4.5$), however, exchangeable Al is the major cation occupying a significant proportion of the effective cation exchange capacity (CEC) (Kamprath, 1970).

It is increasingly being recognized that although acid soils in Rwanda occupy approximately 45% of the total arable land, 60% of the highlands areas are covered by acid soils with pH less than 5.5 (Beenart, 1999). Plant growth and production in these soils is limited by increasing depletion of nitrogen (N), P, Ca and Mg, high P adsorption (1,500 to 3,000 $mg\ kg^{-1}$ of soil), low permanent charge (-0.5 to $-2.45\ cmol\ (+)\ kg^{-1}$) and Al toxicity (Mutwewingabo, 1989). Although soil fertility depletion occurs throughout Africa, it is more acute in Rwanda where annual losses of 54, 20, and 56 kg of N, P_2O_5 and $K_2O\ ha^{-1}\ year^{-1}$, respectively have been estimated, due to overexploitation of natural resources and increased cultivation of marginal areas (Vander Zaag, 1982; Stoorvogel and Smaling, 1990).

Although restoration of the fertility of acid soils can be achieved through widespread application of fertilisers/fertilisation (i.e. inorganic and organic fertilisers) and liming, the use of inorganic fertilisers by the resource-poor farmers can be limited by their high prices, unavailability, associated pollution problems, and inefficient use caused by erosion and leaching losses, denitrification and volatilisation (Tisdale *et al.*, 1990).

Application of lime has been shown to reduce Al toxicity, improve pH, Ca, Mg and increase both P uptake in high P fixing soil and plant rooting system (Black, 1993). As exemplified by Beenart (1999), application of 2 tons ha⁻¹ of burned lime together with 300 kg NPK (17%:17%:17%) ha⁻¹ resulted in maize yield of 5 t ha⁻¹. Burned lime is used by a limited number of smallholder farmers to overcome soil acidity in Rwanda. The report by Rutunga and Mutwewingabo (1987) indicated that the optimum liming rate able to raise pH above 5.5 in acidic soils of Rwanda range between 2-4 t ha⁻¹ of burned lime. Due to the high prices of burned lime and its negative impact on environment, the use of low cost and locally available ground unburned liming materials alone or in combination with organic fertilizers, seem to be a practical option. Since 540 kg of fuelwood are required to produce 1 t of burned lime (Beenart, 1999), the use of ground unburned lime may play an important role in environmental conservation compared to burned lime.

In the past the Rwandan smallholder farmers tried to replenish soil fertility by using the traditional shifting cultivation and fallowing systems, farmyard manure, crop

residues, compost, chicken manure and other animal wastes. Today, however, the traditional farming systems in Rwanda are constrained by the prevailing soil fertility problems caused by population increase which reduced farm size (70% of the families own farms of < 0.5 ha) and or land scarcity and increased overcropping of fertile lands, shortening fallow period, deforestation, overgrazing and erosion.

There is increasing evidence that green manuring, intercropping or crop rotation, alley and contour farming (Nnadi and Haque, 1998; Kang *et al.*, 1990) and improved fallow technologies (Balasubramanian and Sekayange, 1992) can restore soil fertility (i.e. increase N, P and K availability for plant uptake) and maximize agricultural crop production by the resource poor farmers in Rwanda. In addition to these benefits of organic inputs, the decomposition of organic materials are known to ameliorate heavy metal toxicities (e.g. Al and Mn) through complexation reactions by the organic acids and other by-products released in the process (Zaharah and Bah, 1999). Furthermore, the Ca and Mg also released are known to reduce Al saturation on the exchange complex (Zaharah and Bah, 1999). Since for better plant growth 800 kg ha^{-1} of P are required to maintain an optimum P concentration of 0.2 mg kg^{-1} soil in the acid soil solution in Rwanda, the use of organic N and locally available phosphate rocks (PR) and inorganic P fertilisers (Juo and Fox, 1977; Mutwewingabo, 1987) may give a good solution for low crop yields in the acid soils of Rwanda.

Although PR application has shown tremendous potential in improving crop yield and soils properties in acid soils (Chien *et al.*, 1980) evidence exist to show that

short-term crops may not always benefit from these P-sources due to their relatively low reactivity (Zaharah and Bah, 1977). This, therefore, implies that adequate attention needs to be paid on the type of PR to be used. Variable results on reactivity of PR can be attributed to differences in their P composition, solubility and suitability as sources of P. The Minjingu phosphate rock (MPR) from Tanzania and Busumbu phosphate rock from Uganda are among the most suitable sources of P (Van Kauwenberg, 1991; Van Straaten, 1997). Sustainable food crop production in smallholder farmers can, however, be achieved through proper use of MPR (Semoka and Mkeni, 1986; Ngatunga *et al.*, 1989; Buresh *et al.*, 1997) or other PR, limestone and organic fertilisers (Ni *et al.*, 1990; Rajan *et al.*, 1991; Clark *et al.*, 1993; Baligar *et al.*, 1997).

Green manure addition to the soil supplied with P was reported to increase the amount of P released in soil solution and its efficiency by agricultural crops (Nziguheba *et al.*, 1998). The positive effect of mixing soil amendments, such as organic N sources, e.g. farmyard manure and composts, with PRs is widely reported (Bangar *et al.*, 1985; Yang *et al.*, 1994; Gachengo *et al.*, 1999). It is worth noting, however, that the amount of P from PR taken up by plants and crop yield depend on the extent of PR dissolution, P-soil interactions and type of crop (Sanchez, 1997).

Although it is increasingly recognised that limestone, MPR and green manures such as *Tithonia diversifolia* (Tithonia) and *Tephrosia vogelii* (Tephrosia), which are widespread in Rwanda are of low cost and safe (Beenart, 1999; Nabahungu *et al.*,

2002), very little is known about the effectiveness of Tithonia and Tephrosia manures in regulating P release and uptake from MPR and lime added to acidic soils of Rwanda.

The general objective of the present study, therefore, was to investigate the interactive effects of limestone, Tithonia/Tephrosia green manures on soil fertility and maize yield in Rwanda. The specific objectives of this study were:

- i. To evaluate the effect of limestone, MPR and green manures (Tithonia and Tephrosia) on soil nutrients availability and uptake by maize plants.
- ii. To evaluate the effect of limestone, MPR and green manures on soil acidity (pH), Al, H, organic carbon and total P in the soil.
- iii. To assess the effect of Tithonia and Tephrosia green manures on MPR dissolution.
- iv. To determine the optimum rate of limestone application for maximising P use efficiency by maize and establish a suitable combination of the three amendments above.

It was hypothesized that proper combinations of limestone, MPR and green manure will result in improved soil fertility, crop growth and yield.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Soil and acidity

An acid soil is defined as a soil having a pH value below 7.0 (Uriyo *et al.*, 1979) but interpretation for such soils depends on the degree of acidity. Acid soils are commonly found in areas where precipitation is high enough to leach out appreciable amounts of exchangeable bases from the surface layers of soils and their places being taken up by exchangeable H^+ and Al^{3+} (Cochrane and Sanchez, 1982). Consequently, acid soils generally have low percentage base saturation. Cochrane and Sanchez (1982) estimated that 81% of the land area under native vegetation had surface soil layers with pH less than 5.3. Meanwhile 75% and 46% of these soils have Al saturation greater than 40% and exchangeable Ca less than $0.4 \text{ cmol } (+) \text{ kg}^{-1}$, respectively.

Soil acidity is a major constraint to crop production in many parts of the world. Some of the major limitations to crop production in acid soils include toxicity due to aluminium and manganese and deficiencies of calcium, magnesium, potassium and phosphorus (Jackson, 1967). Aluminium toxicity has been found to be a problem in many acid soils in the tropics (Cochrane and Sanchez, 1982). Direct yield reductions are often observed at concentration of soil solution aluminium above $37 \text{ } \mu\text{M}$ and soil Mn levels greater than $148 \text{ } \mu\text{M}$ (Cochrane and Sanchez, 1982).

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Subsoil acidity, having high levels of exchangeable Al, is of major concern in crop production in many regions of the world (Cochrane and Sanchez, 1982). When low pH and high concentrations of Al in the subsurface soil solution persist, root development is dramatically inhibited for many crops such as alfalfa, clover, cotton and barley (Foy, 1974; Foy *et al.*, 1978). In such soils root systems are restricted to the upper few centimetres of the soil profile, making plants vulnerable to moisture stress even during short periods of drought (Mtenga, 2000).

2.2 Problems of the acid soils in Rwanda

Rwanda is a highly populated country with a high degree of soil fertility degradation, which constitutes one of the limiting factors for its agricultural production. Low crop yield in Rwanda is a serious problem mainly due to low soil organic matter, low nutrient contents and high soil acidity. This is caused by overpopulation, which leads to over-exploitation of fertile lands, short fallow periods, destruction of soil organic matter through burning, exportation of all farm residues, and soil losses through erosion (Gillet and Brogniez, 1991; Mutijima, 1997).

It was widely believed that acid soils in Rwanda are located exclusively in the high altitude zone, but recent data have shown that many areas in the intermediate altitude zone also have acid soils (Ndolimana, 1990). Cultivated acid soils with pH<5.5 in Rwanda are estimated to cover 600,000 ha (49% of total cultivated area). Although having the same management problems, the high altitude areas (> 1,800 m) and the middle altitude zone (1,500 - 1,800 m) or the Central Plateau and western zone are

different with respect to types of crops and potential productivity. MINIPLAN (1991) reported that about 46% of cultivated land has $\text{pH} < 5.1$, exchangeable Al $> 2 \text{ cmol (+) kg}^{-1}$, exchangeable Ca between 1.5 to 2 cmol (+) kg^{-1} , exchangeable Mg^{2+} between 0.2 to 0.3 and exchangeable K between 0.08 to 1.5 cmol (+) kg^{-1} .

Mujyebumba (1997) suggested that soil fertility in Rwanda can be improved through application of inorganic and organic fertilisers, recycling of household waste, improving the quality of compost as well as managing the acid soil with ground limestone (i.e. neutralising or decreasing Al to non toxic and increasing the content of exchangeable calcium and magnesium in the soils).

The use of mineral fertiliser by the smallholder and resource poor farmers in Rwanda may be limited by their high prices and unavailability and the lack of sufficient knowledge about the types, times and rates of application (Bazivamo, 1998).

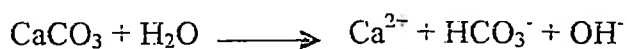
The soils of Rwanda present favourable conditions (low P, pH, Ca and high rainfall) for effectiveness of MPR as a source of P. It was indicated in Tanzania that under conditions of low pH, P, Ca and high rainfall, MPR was as effective as conventional P fertilisers (TSP) (Mowo, 2000).

2.3 Soil acidity and liming

The negative effects of soil acidity with regard to plant growth and development can be corrected by liming. Liming is considered for strongly acid soils ($\text{pH} < 5.0$) and the

practice rarely aims at increasing the pH to 7.0. Liming, in the tropics, is a practice of adding any material to acid soils with the purpose of neutralising exchangeable Al and creating favourable soil conditions and environment for plant growth and microbial activities (Uriyo *et al.*, 1979). Liming materials are used, not only to raise the pH of acid soil and lower soluble Al, but also to increase the quantities of exchangeable and soil solution Ca, Mg, P and N. Liming of acid soils enhances the availability and plant uptake of nutrient elements such as molybdenum, phosphorus, calcium and magnesium. At the same time, liming drastically reduces the concentration of exchangeable Al, Fe and Mn, which under very acid soil conditions are likely to be present in toxic levels in the soil solution and on the exchange sites (Uriyo *et al.*, 1979).

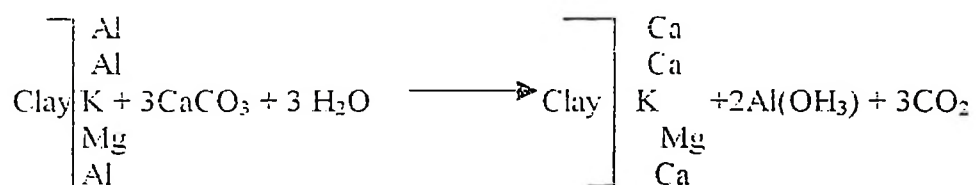
Liming reactions begin with the neutralisation of H^+ in the soil solution by either OH^- or HCO_3^- originating from the liming material (Tisdale *et al.*, 1993). For example, $CaCO_3$ behaves as follows:



The rate of the reaction is directly related to the rate at which the OH^- ions are removed from the solution. As long as sufficient H^+ ions are in the soil solution, Ca^{2+} and HCO_3^- will continue to go into solution. When the H^+ ion concentration is lowered, however, formation of Ca^{2+} and HCO_3^- ions is reduced.

The continued removal of H^+ from the soil solution will ultimately result in the precipitation of Al^{3+} and Fe^{3+} as $Al(OH)_3$ and $Fe(OH)_3$ and their replacement on the exchangeable sites by Ca^{2+} and/or Mg^{2+} .

The overall reaction for neutralization of Al-derived soil acidity can be written as follows:



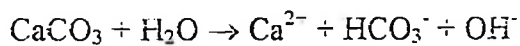
Obviously, as pH increases, the percent base saturation also increases (Tisdale et al., 1993).

Liming of acid soils maintains and sustains the fertility status of soils if the cropping system is well managed. However, in poorly managed cropping system liming may act as a stimulant, producing good crops immediately, followed by gradual decline of the fertility status of the soil (Uriyo *et al.*, 1979).

2.4 Effect of liming on phosphorus availability

Generally, soils with low pH have low available P levels and liming such soils would increase phosphate availability to plants (Sanchez and Uehara, 1980). Several reasons have been given to explain the increase in extractable P after liming. In acid soils, variscite ($AlPO_4 \cdot H_2O$) followed by strengite ($FePO_4 \cdot 2H_2O$) are the most stable

P minerals in soils. Liming will increase soil pH and result in the hydrolysis of strengite and variscite with the release of phosphate ions into the soil solution (Haynes, 1982). Holford (1983) and Ryan and Smillie (1975) found that liming increased P in the soil solution and attributed the increase to the hydrolysis of Fe and Al phosphates due to the increase in soil pH. This increased phosphorus uptake by Italian ryegrass from 7.3 to 9.9 mg pot⁻¹. Hemphill and Jackson (1982) reported that liming increased pH from 5.1 to 6.6. The P concentration in beans increased from 0.21 to 0.32%. This implies that, P increased in the soil solution and its uptake by bean plants was also increased and hence increasing its tissue concentration. Liming an acid soil reduces the phosphate retention capacity of the soil and this can be explained by the liming reaction:



Where both the HCO_3^- and OH^- can compete with phosphate for the anion retention sites on the soil colloids. These anions are specifically retained onto active soil surfaces. The OH^- also increases the magnitude of the negative charge sites on the soil colloids, hence reducing phosphate retention by the soil colloids (Mackay and Syers, 1986; Haynes, 1982).

Liming may also increase P availability in the soil by decreasing the adsorption of phosphates by soils colloids (Haynes, 1982). It has been reported that phosphate adsorption by soil is maximum in the pH range of 2 to 4 (Obihara and Russell, 1972;

Perfitt, 1978; Bowden *et al.*, 1980). The phosphate ions are usually adsorbed on Fe and Al oxides mainly as HPO_4^{2-} rather than H_2PO_4^- (Bowden *et al.*, 1980; Taylor and Ellis, 1978). When pH increases, say from 2 to 7, the concentration of HPO_4^{2-} ions increases in the soil solution (Kwong *et al.*, 1979) because liming decreases the adsorption of phosphate by soil colloids. Smyth and Sanchez (1980) observed in Brazil that liming a kaolinitic acid soil in which P was previously applied decreased P fixation by decreasing the previous amount of P sorbed and increased solution P by 18 - 24%.

Another important factor, which contributes to increased P availability with liming, is the increase in the microbial processes in the soils after liming (Kennedy, 1986). Liming acid soils increases soil pH to a favourable range where soil microorganisms namely bacteria and actinomycetes can accelerate decomposition of organic matter and hence releasing inorganic phosphate and other ions into the soil (Kennedy, 1986). However, excessive liming should be avoided since liming soils to pH 6.8-7.0 can reduce P availability because of the precipitation of insoluble Ca or Mg phosphates (Tisdale *et al.*, 1993).

Several workers (Awan, 1964; Halstead *et al.*, 1963; Singh, 1989; Thompson *et al.*, 1954) have reported that liming increased available P in the soil. Awan (1964) observed a significant increase in available P following liming and P additions. By applying 35 kg P ha^{-1} , the available P in soil increased to 6.7 mg kg^{-1} . But the addition of 2 t ha^{-1} of lime in combination with the above P rate increased the

available P to 12 mg kg^{-1} . Similarly Singh (1989) working in Zambia found that application of 4 t of lime ha^{-1} increased the available P in soil from 26 to 32 mg kg^{-1} . It was further observed that addition of 4 t ha^{-1} of lime combined with 33 kg P ha^{-1} to the soil increased available P to 60 mg kg^{-1} .

2.5 Exchangeable aluminium as a criterion for lime requirement

In theory, numerical values of measurements of any of the plant growth factors affected by liming could be plotted against the quantity of calcium carbonate added to determine the quantity required to produce the desired response. Because of the great importance of aluminium toxicity in strongly acid soils, it is logically the first specific plant growth factor that comes to mind as a possible alternative to soil pH as a criterion for the biological lime requirement (Black, 1992).

The possible value of aluminium as a criterion for the biological lime requirement is suggested by different kinds of evidence. One is the existence of marked difference among crops in sensitivity to aluminium at a given pH value. For example, Hetherington *et al.* (1988) cited by Black (1982) found that in culture solutions maintained at pH 4.2, the relative sums of the activities of monomeric species of aluminium in micromoles per liter associated with a 10% reduction in relative root length were 1.0 for navy bean, 1.8 for corn, 2.0 for soybean, and 16 for sugarcane (means for three cultivars).

A second form of evidence suggesting the value of aluminium as a criterion for the biological lime requirement is the existence of response curves indicating maximum yields of some crops at low pH values that seem to be related to the chemical behaviour of aluminium in soils (Evans and Kamprath, 1970; Reeve and Summer, 1970; Mehlich, 1976; Farina *et al.*, 1980)

The importance of aluminium toxicity was behind the proposal by Kamprath (Kamprath, 1984; 1990) to use elimination of aluminium toxicity instead of pH as a criterion for determining when the biological lime requirement has been satisfied. For highly weathered and leached soils, he recommended adding a quantity of calcium carbonate equivalent to 1.5 times the content of exchangeable aluminium for general crops or 2 times the content of exchangeable aluminium for very sensitive crops. According to Kamprath (1984), these additions will reduce the aluminium saturation to the exchange capacity to practically zero and will supply adequate amounts of calcium plus magnesium. The excess of calcium carbonate over the exchangeable aluminium is needed because of some originally non-exchangeable aluminium appearing in exchangeable form when the exchangeable aluminium is removed.

2.6 Carbonate rocks of Rwanda as liming materials

Rwanda has large reserves of travertine and dolomitic rocks and the exploitation of the main deposits is possible (Beenart, 1999). Liming products (ground travertine and more or less burned limes) are at present almost exclusively produced in large quantity near

Ruhengeri and at Mashyuza (Cyangugu). The annual production is 9,000 ton/year (MMCF, 1993). Although, travertine and dolomite, reserves are abundant in Rwanda, only 30 % are coherent rocks, required for the production of lime. The remaining 70 % occur as loose sandy travertine, which is not suitable for lime production. From an agronomic and economical point of view, therefore, it would be logical to reserve the coherent rock fraction for lime production (i.e. for construction) and to exploit the sandy fraction for agricultural purposes, using a more simple and low cost treatment (MMCF, 1993). Very often, there is more variation in the CaO and MgO content of travertine of the same deposit, as compared with travertine of different deposits. According to Munyangabe (1993), the average maize yield increased from 0.6 tonne/ha in the control to 1.8 t ha⁻¹ by applying 4 t ha⁻¹ of travertine.

2.6.1 Travertine group

Travertine is limestone with high Ca content (CaO>40%) and low magnesium content (MgO<3%). Travertine is found in recent formations of Pleistocene Age and is a less compact, soft rock, which is easily extractable without explosives. Beenart (1999) reported that, travertine has a cationic (Ca/Mg) ratio of 13-15 which is much higher than the optimal ratio of 4-5. This might cause disequilibria in the cation balance and affect soil fertility (Beenart, 1999). Kayonga and Goud (1989) observed that ground travertine rocks raised soil pH by 0.5 pH units, reduced exchangeable Al, increased base saturation, and introduced disequilibria between the exchangeable cations. These rocks have a suitable chemical composition to eliminate aluminium toxicity in acid soils but cause nutrient imbalance and hence create new problems.

2.6.2 Dolomitic rocks

Dolomitic rocks are limestones with high content of magnesium (CaO 30%, MgO 20%). The dolomitic rocks of Rwanda include dolomitic limestone, dolomitic marbles (Mbarara island) and dolomites (Gillet and Brogniez, 1991). These are hard rocks used for building construction and which need explosives and more sophisticated cutting, drilling and grinding equipment, for their extraction.

Although records show the existence of very large reserves of dolomite deposits in Kibuye (Gillet and Brogniez, 1991), very little is known about their agronomic efficiency. The report by Wouters and Gourdin (1989) showed that dolomite rocks can successfully eliminate soil acidity and Al toxicity but their chemical composition with a cation (Ca/Mg) ratio close to 1 is not suitable for agriculture.

2.7 Phosphorus sorption by soils

Phosphorus sorption by the soil has been defined by Sanchez (1976) as the removal of soluble phosphate from solution by a soil or soil constituent followed by its concentration in the solid phase. Sorption of P occurs mainly on hydrous oxides of Al and Fe and at the surface of layer silicate clay particles (Frossard *et al.*, 1995 cited by Buresh *et al.*, 1997), which increases in importance in soils with increasing weathering and clay content (Sanchez and Uehara, 1980). It is a dominant process controlling P availability in Ultisols and Oxisols with medium to fine textured topsoils (Sanchez and

Uehara, 1980). Studies have shown that P sorption is influenced by soil properties such as pH, CEC (Hue, 1992), P status of the soil (Sanchez, 1976), clay content (Sanchez and Uehara, 1980), type of clay minerals and organic matter (Iyamuremye, 1996), temperature and time of reaction (Moshi *et al.*, 1974 cited by Savini, 199).

Sorption of P is a problem in many tropical soils because of large quantities of oxides Al and Fe and 1:1 clays present in many highly weathered soils (Sanchez and Uehara, 1980). The large contents of Al and Fe oxides result from weathering. These oxides carry positive charges at pH values below 5 (Brady and Weil, 1996). In addition, kaolin, which is a prevalent clay mineral in many tropical soils, carries positive charges thus enhancing the P sorption capacity of these soils (Moshi *et al.*, 1974 cited by Savini, 1999).

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

To some degree, the above P fixing soil components are widely distributed in soils and are related to soil taxonomy. Vertisols and Mollisols generally are dominated by 2:1 clays and have low P fixation capacities. Iron and Al oxides are prominent in Ultisols and Oxisols and cause high P fixation in these soils. Andisols, characterized by large

quantities of amorphous oxides and allophane have the greatest P fixing capacity, and their productivity is often limited by this property.

Smyth and Sanchez (1982) and Mackay *et al.* (1996) found that, the dissolution of PR increases as soil P-sorption capacity increases, but extractable P decreases with increasing soil P-sorption capacity (Syers and Mackay, 1986; Kanabo and Gilkes, 1987). The short-term agronomic effectiveness of both PR and soluble P fertilizer decreases with increasing P-sorption capacity due to decreasing soil solution P (Mokwunye and Chien, 1980; Hammond *et al.*, 1986). Although a high P-sorption capacity can provide more rapid dissolution of PR, the low soil solution P concentration resulting from high P sorption may limit plant growth (Mokwunye and Hammond, 1992).

Mnkeni and Mackenzie (1985) observed a decrease in P sorption resulting from addition of plant residues or farmyard manure to upland topsoil. The reduction of P sorption due to organic amendments in soils is undoubtedly the cumulative effect of many mechanisms. However, insights into the relative importance of these mechanisms were reported by Iyamuremye *et al.* (1995a), who compared organic amendments with inorganic amendments. Calcium carbonate decreased exchangeable Al and increased pH while CaSO_4 decreased exchangeable Al but had no effect on soil pH. Both of these inorganic amendments had less effect on sorption constants compared to P rich organic residues (manure and alfalfa). Calcium carbonate and calcium sulphate did not increase total inorganic P, as did organic

amendments. Iyamuremye *et al.* (1995c) concluded that the production of organic acids or organic complexing agents and their effect on P fractions were more important than reduction in exchangeable metals in affecting P sorption when soils were amended with organic residues. Furthermore, wheat straws with low P content also increased P in equilibrium solution and decreased sorption capacity in most of the soils studied, which suggested that other compounds or mineralisation products in residues, such as organic acids, are involved in preventing P sorption.

2.3 Technologies for supplying nitrogen

Green manuring and/or mulching are some of the practices employed to replenish nutrients in agroforestry systems. These practices may ensure slow and continuous release of nutrients (Nair, 1993). However, addition of these plant materials on soils deficient in nutrients does not automatically guarantee nutrient release. It is generally accepted that nitrogen and phosphorus are mineralised more easily than carbon when the ratios between C/N and C/P in a given substrate exceed certain critical values (Nair, 1993). Otherwise relative scarcity of N and P occur and microorganisms tend to immobilise both elements for use in their own metabolism (Budelmann, 1988). Therefore, some plant species in agroforestry systems provide low quality litter while others provide high quality litter (Nair, 1993). The term quality here refers to nutrient content and comparative rate of decomposition as defined by Nair (1993). Traditionally high quality litter is one with high nitrogen content and relatively low carbon content and hence decomposing relatively fast (Alexander, 1961). Thompson and Troel (1979) pointed out that, it takes longer for the mineralisation stage to be

reached for materials with wide C:N ratios than for those with narrow ratios. Handayanto *et al.* (1994) added that addition of organic substances with C:N ratio wider than 30:1 result in immobilisation of soil nitrogen during the initial decomposition process. The dividing line between immobilisation and release of N is at C:N ratio of approximately 20:1 (Handayanto *et al.*, 1994).

Woody residues and other lignified materials e.g. cereal straws or plant materials with high content of fat and wax have wide C:N ratios. Consequently, they are of low quality and decompose slowly (Nair, 1993). Budelman (1988) found a close relationship between decomposition rate and C:N ratios of different plant species. He reported that the half-life value of fresh leafy biomass of *Leaceana leucocephala*, *Gliricidia sepium* and *Flemingia microphylla* all with a C:N ratio of 12:1 were 31, 22, 53 days, respectively. Therefore, to improve efficiency of nutrient utilisation by crop there is a need to synchronise nutrient release from mulch and green manure with critical period of high nutrient demand by crops, example 4 – 6 weeks for maize (Lehman *et al.*, 1995). In an effort to slow down decomposition of fast decomposing *Gliricidia sepium*, Nduwayezu (1997) found that mixtures of *Gliricidia* leaves and sawdust with C:N ratios of 21:1 and 29:1 applied on soil, synchronised the time of N release with plant requirements. This led to increase in maize yield compared to the absolute control and where *Gliricidia* (C:N = 13:1) or sawdust (C:N = 29:1) were applied alone. However, Nduwayezu (1997) did not determine the contribution of *Gliricidia* to the P status of the soil.

The C/P ratio of the decomposing residues regulates the predominance of P mineralisation over immobilisation, just as the C/N ratio regulates N mineralisation / immobilisation relations (Tisdale *et al.*, 1993). The critical upper value for C/P ratio is not well established, however the following guidelines have been suggested (Tisdale *et al.*, 1993): Net mineralisation of organic P occur if the C/P ratio is < 200 . Between 200-300, there is no gain or loss of inorganic P. Net immobilisation of inorganic P occurs if the C/P ratio is > 300 . In a sorption-desorption study, Singh and Jones (1976) found that net P immobilisation occurred with materials having P content $< 0.3\%$. Tisdale *et al.* (1993) added that net P immobilisation occurs with residues low in P content ($< 2\%$ P) during the early stages of decomposition followed by net P mineralisation as the C/P ratio decreases.

An additional benefit of green manure is the importance of plant biomass in P availability in soils, which can be summarised in three ways. One of the benefits of the biomass is the reduction in P sorption of the soil (Nziguheba *et al.*, 1998; Singh and Jones, 1976) leading to improved P availability to growing plants. Secondly, is the enhancement of the dissolution of sparingly soluble P sources leading to an increase in the available P content of the soil (Nye and Kirk, 1986; Sale and Mokwunye, 1993; Flash *et al.*, 1987). The third contribution is the actual addition of P from decomposing plant biomass (Buresh *et al.*, 1997; Haggard *et al.*, 1991; Gachengo, 1996).

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2.3.1 Biomass transfer

Biomass transfer refers to the practice where organic materials are produced elsewhere and carried to the site. This, result on an actual addition of nutrients to the site (Palm *et al.*, 1997). The leaf biomass of trees is frequently cut from hedges or uncultivated areas and incorporated to crop fields as a source of nutrients in Africa (Palm *et al.*, 1997). While the quantities of biomass farmers are able to apply are often sufficient to supply N to a crop maize with a moderate grain yield (about 4 t ha⁻¹), they seldom can supply sufficient P to that crop (Palm, 1995). Leguminous trees are most frequently used in biomass transfer systems but there is increasing evidence that some non-leguminous shrubs may also accumulate high concentrations of nutrients in their biomass. Tithonia, for example was reported to have unusually high concentrations of N (3.5%), P (0.38%) and K (4%) in its leaf biomass (Gachengo, 1996; Niang *et al.*, 1996). Meanwhile the N, P, K contents of *Vernonia subligera* a shrub commonly used in north east of Tanzania for soil fertility management are respectively 3.6%, 0.25% and 4.7% for N, P, K (Wickama and Mowo, 2001). These P and K levels are higher than those of commonly used leguminous plants in agroforestry (Palm, 1995). Reasons for such high concentrations remain speculative but members of the Compositae family, to which Tithonia belongs, have a reputation of being nutrient scavengers. Although the processes involved are not presently identified, they may probably involve the dissolution of inorganic phosphorus, desorption of fixed soil phosphorus by root exudates, organic acids and/or extremely effective mycorrhizal associations. Woody species grown in hedges outside the cultivated fields, therefore, may be able to transform less available organic forms of

P, as well as supply significant quantities of N and K, when their leaves are incorporated into the soil by biomass transfer (Palm *et al.*, 1997).

Tephrosia is a leguminous plant adapted to a wide range of conditions ranging from dry to moist tropics (500-2500 mm annual rainfall) (Milne-Redhead and Polhill, 1971). The chemical constituents of Tephrosia are 2.85-4.0% N, 0.38% P, 1.03% K, 1.89% Ca, 0.16% Mg, 8.0-8.3% lignin, 2.37% polyphenols, 21.1% cellulose and 0.97% rotenones (Hagedorn *et al.*, 1997; Mlutuo *et al.*, 1998; TSBF, 1999). Based on these chemical constituents and on characterisation of organic materials by Palm *et al.* (1997), the biomass of Tephrosia is classified as a high quality organic material. However, the nutrient release rate of Tephrosia is gradual and could thus be used as a source of nutrients for a period of time. According to Fasuluku (1998), the N mineralisation rate of Tephrosia is relatively slower compared to *Sesbania sesban*. The author demonstrated that about 33% of N in its foliage was mineralised during the first four weeks and thereafter N release decreased gradually to the tenth week. The total P released during the same period was about 12.9 kg P ha⁻¹ after fallow.

In Rwanda, Balasubramanian and Sekayange (1992) observed that at Kagasa (soil pH 5.1 and relatively dry area in Rwanda, mean rainfall 1100 mm), one year of Tephrosia fallow accumulated dry weight equivalents of 4.8 t ha⁻¹ of leaf litter and 2.6 t ha⁻¹ of foliage. The two components of biomass added a total of 238 kg N ha⁻¹ year⁻¹ to the soil. On Ferralsol in Southern Rwanda (mean rainfall = 1400 mm year⁻¹), Hagedorn *et al.*, (1997) reported biomass of Tephrosia of up to 6.6 t ha⁻¹ when

relayed with sorghum which when applied at 2.7 t ha^{-1} , released 112 kg N ha^{-1} . In Western Kenya, Rutunga *et al.*, (1999), observed that a six months old Tephrosia fallow produced 9.5 t ha^{-1} that accumulated 154 kg N ha^{-1} .

2.9 Potential of phosphate rock use in highly weathered soils

A number of research results have indicated the potential of phosphate rock (PR) for direct application in agriculture. Jaggi (1986) reported results of experiments carried out in acid soils in which phosphate rock was found to be as effective as or better than superphosphate in increasing paddy yield. He reported comparable yields of gram, slightly lower yield of wheat and slightly higher yields of groundnuts in Ultisols and their integrades in Bihar when phosphate rock was compared to superphosphate. Budotela (1995) using MPR observed an increase in the number of clusters per vine and subsequent grape fruit yield compared to control. Buresh *et al.* (1997) working with MPR and superphosphate found higher yield of maize following incorporation of TSP or MPR (as sources of P) with Tithonia rather than urea at an equivalent N rate. They further noted that the benefit of Tithonia was partially attributed to K and to addition of about 15 kg P ha^{-1} . Mnkeni *et al.* (1991) working with four different soils observed varied effects of MPR on maize yield. Application of 80 and 240 kg P ha^{-1} significantly increased maize yield on Magadu and Mzumbe soils both with $< 6.5 \text{ mg P kg}^{-1}$ and pH value < 5.2 . However, response to MPR application was neither observed on Mafiga 1 soil with comparable P levels as the above two soils nor on Mafiga 2 soil with slightly higher P level but where pH values were > 6 .

2.10 Some previous phosphate rock incubation studies

Mnkeni *et al.* (1992) working with two soils from Morogoro Tanzania (pH 5.5, and 6.2) incubated with MPR (added 400 mg kg⁻¹ for Magadu 1 soil and 36 mg kg⁻¹ for Magadu 2 soil) found that there was considerable dissolution of MPR in the soils and that extractable P values increased with increase in incubation time. Tusekelege (1997) however gave different results from those obtained by Mnkeni *et al.* (1992). Working with three soils (pH. 4.7; 5.2; 5.3) she found that extractable P from MPR increased up to the seventh day of incubation and thereafter decreased.

Mandal and Khan (1972) observed a gradual increase in Bray 1 P from 200 g of soil treated with PR, attaining the highest level after 60 days of incubation. The extractable P values were lower with single superphosphate than with PR at 60 days of incubation. They also noted that addition of one gram of rice straw or berseem (*Trifolia elaxandrin*) hay led to further increase in P release from the two sources. However, the workers did not give important chemical characteristics such as P, C and N content of the organic materials. Dashrath and Datta (1973) working with Mussorie PR in an acid soil observed a higher value of Bray 1 P at 49 days of incubation than at 14 days. The Bray 1 P was observed to attain maximum at 77 days of incubation.

2.11 Minjingu phosphate rock

In recent years there has been renewed research interest on the use of phosphate rocks (PR) in Tanzania. MPR being of sedimentary origin (Mnkeni *et al.*, 1992) has

moderate to high agronomic effectiveness compared to other PR sources as rated by Semoka *et al.* (1992). MPR was reported to be more reactive than Panda PR (Mnkeni *et al.*, 1992). Semoka and Kalumuna (1999) made a comprehensive review of PR research work conducted in Tanzania since the 1960's. The review showed promising agronomic effectiveness of MPR. Under favourable conditions of low pH, P, Ca and high rainfall, MPR was as effective as conventional fertilisers (TSP). In most cases, conventional fertilisers were better than MPR in the first season of application but in subsequent seasons the effectiveness of MPR increased (Semoka and Kalumuna, 1999). PR application has been reported to increase both P and Ca uptake by plants in P deficient soils (Hammond *et al.*, 1986). According to Mnkeni *et al.* (1992) MPR has the potential of releasing P when incubated with soil or applied directly in low P, low Ca, and acidic soils of Tanzania. It is widely believed therefore, that the increased Ca and P uptake following application MPR is a result of enhanced supply of Ca and P in the soil solution. Many workers have reported sedimentary PRs to be more reactive than igneous and metamorphic PRs (Khasawneh and Doll, 1978).

Crop responses to a given fertiliser material is a good measure of its effectiveness. Studies on an Ultisol (Ikerra, 1986) and on acid sandy loam soils (Ngatunga *et al.*, 1989) showed that MPR and TSP had similar effect on P availability to maize and sorghum, respectively.

2.12 Role of organic amendments on soil phosphorus

Maintenance of adequate orthophosphate in soil solution for plant growth is controlled by both chemically and biologically mediated reactions. Ghoshal (1975) studied the competition between these two mechanisms for controlling soil solution orthophosphate and concluded that generally chemical reactions dominate in soils. However the microorganisms play a critical role in mineralisation of organic inputs and partitioning P into various organic fractions and contribute to the continuous supply of orthophosphate into the soil solution during the growing season.

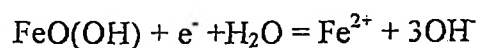
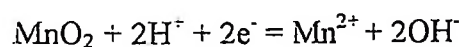
According to Iyamuremye and Dick (1996), as early as the turn of the century many workers recognized that organic amendments enhanced the utility of phosphate rock, affected P retention in soils and availability to plants. Dalton *et al.* (1952) cited by Savini (1999) attributed the increase in the availability of soil P to microbiological decomposition of organic amendments, which release metabolic products to form stable complexes with Fe and Al in acid soils.

The main supply of P in the soil is through the incorporation of plant or animal residues and waste and through the application of chemical fertilisers. Any organic matter technology may be thought of as a P technology, although in general, the emphasis has been to use organic matter technologies to supply N or soil organic matter, rather than to use them for the specific objective of increasing soil P. However, some species can alleviate P deficiency in the soil, e.g. *Tithonia* through biomass transfer or improved fallow. Jama *et al.* (2000) found that the major method

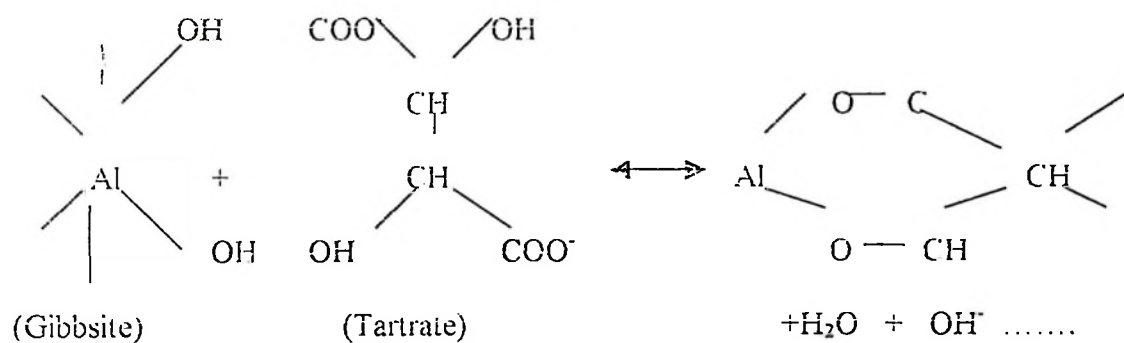
for using Tithonia as a P-mobilising technology is in biomass transfer system. The P release from green biomass of Tithonia is considered to be “at least as effective as an equivalent supply of P from soluble fertiliser” (Jama *et al.*, 2000). Tithonia is also considered to increase the pools of labile P. Experiments at Nyabeda and Kwisero in Western Kenya showed that maize yields from Tithonia were at least as high as those from soluble P, and often higher than the yield from mineral fertiliser when applied in equivalent quantities. The mean N content (3.5%) and P content (0.37%) are above the levels at which net N and P immobilisation generally occur (2.5% for N and 0.25% for P) (Jama *et al.*, 2000).

2.13 Role of organic amendments on Soil pH

Addition of plant residues can cause significant increase in soil pH (Hoyt and Turner, 1975). Hue (1992) and Mkeni and MacKenzie (1985) obtained higher pH values in soil solutions treated with organic residues than in those amended with calcium carbonate. The pH changes have been attributed to the high concentrations of basic cations in the organic matter used (Hue, 1992; Hoyt and Turner, 1975) or Fe oxides and hydrous oxides (Hue, 1992) in soils. The latter reaction leads to the self-liming effects observed in submerged soils caused by oxidation-reduction reactions.



Theoretically, these reactions should not occur in aerobic soils. However, because of the heterogeneity of the bulk soils it is possible that anaerobic microsites occur in aggregates. Hue (1992) also suggested that pH may increase due to ligand exchange between organic acids and hydroxyl groups of Al and Fe oxides as shown below:



The increase in pH causes an increase in CEC, which results in formation of negative charges on colloidal fractions.

2.14 Role of organic amendments on exchangeable aluminium and iron

In acid soils high levels of exchangeable Al and Fe play a significant role in controlling orthophosphate concentration in the soil solution. Thus reduction of exchangeable Al and Fe by organic soil amendments could have a significant effect on P sorption. Iyamuremye *et al.* (1996a) reported that organic amendments (animal manure and plant residue) decreased exchangeable Al on high P fixing soils after a 28-day incubation. Several mechanisms may be involved in decreasing exchangeable cations when organic residues are added to soils. These reductions may be due to precipitation of Al ions released from the exchange of ligands between organic

anions and terminal hydroxyls of Fe and Al oxides, and/or the complexation of Al by organic molecules (Hoyt and Turner, 1975; Hue, 1992).

Organic acids such as oxalic, malic, malonic and citric acids are believed to complex exchangeable Al (Hue *et al.*, 1986 cited by Savini, 1999) and were found to be in greater concentration in forest soil than in agricultural soils. Iyamuremye *et al.* (1996b) detected oxalic, malic, malonic, maleic, succinic, formic and acetic acids in soil solution samples treated with organic residues. Speciation modeling of manure-amended soil showed that citric acid had a major role in complexing Al and Fe and affecting P activity in soil solution (Iyamuremye *et al.*, 1996b).

2.15 Role of organic materials on phosphate rock dissolution and plant availability

Plant availability of P from PR is often enhanced when mixed with organic material such as compost. The extent of solubilisation of a given PR varies with the kind of waste and the rate of decomposition (Bagar *et al.*, 1985; Mahimairaja *et al.*, 1995). Biological activity and production of acid during composting are likely to solubilize PR. A number of studies in India have shown that mixing rock phosphate with animal manure or plant residue followed by composting increased citric acid soluble P and/or P availability to plants (Rostogi *et al.*, 1976). In an alkaline soil, Singh and Amberger (1995) showed that compost enriched with rock phosphate resulted in greater P uptake by ryegrass in the greenhouse and lower fixation with native calcium than soil amended with soluble inorganic P. Work carried out elsewhere

indicates that organic materials could enhance crop utilisation of P from PRs (El-Banna *et al.*, 1978; Chakraborty, 1982; Dhar and Singh, 1982).

Organic matter is known to be among factors that enhance dissolution of PR. According to Hammond *et al.* (1986), organic matter upon hydrolysis may supply some organic functional groups or anions such as citrate or oxalates that can effectively chelate Ca ions, thus lowering the Ca activity in the soil. This in turn provides a driving force for further dissolution of PR. Ikerra *et al.* (1994) observed greater release of P when MPR was combined with compost (58 mg P kg⁻¹) or FYM (74 mg P kg⁻¹) than when MPR was applied alone (45 mg kg ha⁻¹). It has generally been established that aliphatic organic acids, phenols, carboxylic acids and mineral acids are produced during decomposition of OM and composts. These acids, together with carbonic acid in the soil resulting from metabolic wastes of plants roots, micro-organisms and microbial decomposition process in soil help in dissolution of PR (Alexander, 1977; Jaggi, 1986).

One of the problems of P replenishment in Africa is that acidifying agents are likely to be needed to facilitate the dissolution of PR (Buresh *et al.*, 1997). The decomposition of organic inputs produces (i) complexes (chelate) with ions of Fe and Al in the soil solution, preventing the precipitation of phosphate, and also reducing Al and Fe toxicity; (ii) compete with P for sorption sites and/or (iii) solubilize P from insoluble Ca, Fe, and Al phosphates (Palm, 1997). Studies with Kodjari PR in Burkina Fasso (Lompo, 1993) and MPR in Tanzania (Ikerra *et al.*, 1994) confirmed

that mixing PR with compost increased P availability for crop uptake. Also positive results were found when mixing finely ground PR with poultry or cattle manure. The effectiveness of organic manure in controlling P availability can be explained by the fact that organic anions produced during the decomposition of plant materials may temporarily reduce the P-fixation capacity of soil by binding to the Fe and Al oxides and hydroxides at surfaces of clay particles (Iyamuremye and Dick, 1996; Nziguheba *et al.*, 1998). Studies with *Senna spectabilis*, however, showed no effect (Gachengo, 1996). Zaharah and Bah (1997) working with green manures on P solubilisation and uptake from PRs, found that green manures increased the solubility of the less reactive PRs and depressed that of the more reactive ones. This was believed to be through nutrient supply and release of P; and indirectly by decreasing or increasing P fixing capacity. The same observation was reported by Savini (2000) who working with MPR and Busumbu PR, found that MPR combined with *Tithonia* biomass caused depression in anion exchangeable resin P relative to MPR alone. Indeed little is known about the influence of organic materials applied together with inorganic fertilisers on P solubilisation and sorption-desorption processes (Palm *et al.*, 1997).

One of the contradictions is the beneficial effect ascribed to organic manure in enhancing the effectiveness of PR. Most organic manures have alkaline pH. Wong *et al.* (1998) cited by Mowo (2000) observed that farmyard manure like most other organic manure was a good soil acidity ameliorant, high in proton consumption capacity. Given that most PRs are themselves high in pH, Mowo (2000) argued that, mixing them with such manure would lower instead of increasing the amount of

protons available for PR dissolution. Therefore, the positive interactions found when farmyard manure is combined with PR must arise from mechanisms other than proton-induced dissolution of PR. The most likely possibility is chelation of Ca by organic molecules released during decomposition of organic matter. Purnomo and Black (1994) compared incubation for 30 days of the reactive North Carolina PR before sowing with application at sowing, and observed an increased Colwell P concentration but no significant dry-matter yield increase. The length of incubation may be critical; short periods will not ensure enough production of protons or chelating organics while in long periods dissolved P may react with soil constituents, especially in high P fixing soils, making dissolved P unavailable for plant uptake (Mishra and Bangar, 1986; Singh and Amberger, 1991; Iker *et al.*, 1994).

2.16 Combining Inorganic P and Organic Inputs

The main soil source of soluble inorganic P (P_i) is dissolution of primary P minerals, mainly apatite (Buresh *et al.*, 1997). Primary P minerals decrease in soil with increasing soil weathering and are relatively unimportant in highly weathered soils (Smeck, 1985 cited by Buresh *et al.*, 1997).

In acid soils, the sorption of P_i occurs mainly on hydrous oxides of Fe and Al at the surface of layer silicate clay particles (Schewetmann and Harbillon, 1992; Frossard *et al.*, 1995 cited by Buresh *et al.*, 1997), which increase in importance in soils with increased weathering and clay content (Sanchez and Uehara, 1980).

On farm research in moderate P-sorbing Oxisols with pH 5.1 in western Kenya showed the importance of combining inorganic and organic P sources (Sanchez *et al.*, 1997). The combination of Tithonia biomass (1.8 t ha^{-1}) with MPR (250 kg P ha^{-1}) increased maize yields by 400% (from 0.8 to 4.0 t ha^{-1}). This tremendous increase in yield would come from the high concentration of P in Tithonia compared to other green manures. Tithonia also supplied relatively high concentrations of N and K. The benefit from Tithonia is partially attributed to addition of 60 kg P ha^{-1} with the plant material. Subsequent research finding confirmed higher production with the sole application of Tithonia biomass than with an equivalent rate of N-P-K as inorganic fertiliser in a soil deficient in N, P and K (Jama *et al.*, 1997). Techniques to replenish soil P, therefore, consist of P fertilisation combined with the effective use of organic sources.

Almost half of arable soils in Rwanda are acidic, and have a limitation of N, P, K, Ca and Mg. They have high P adsorption and Al toxicities. The routine methods to solve these problems require use of burned lime, and industrial fertilisers that are not affordable by smallholder farmers and in most of cases these methods are not safe for environment. On the basis of research done in Rwanda and elsewhere, a combination of limestone, rock phosphate and green manures may provide a good solution for managing these soils.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials

Soil with pH = 4.7 was used for both field and pot experiments. The test crop was maize variety ZM 607. Fertilisers used both in pot and field experiments were: unburned ground travertine, unburned ground dolomite (CaMgCO_3), Minjingu phosphate rock (MPR), green manure from Tephrosia and Tithonia. The foliage of Tithonia and Tephrosia was collected from the ISAR farm. Samples of the collected fresh biomass were air-dried and ground to pass through a 0.5 mm sieve and their chemical properties determined. Unburned travertine rock was collected from Ruhengeri (North-east of Rwanda) while dolomite rock was collected from Kibuye (North-west of Rwanda). They were ground to pass through 1 mm sieve and mixed in 1:1 ratio (i.e. 50% travertine mixed with 50% dolomite). The Minjingu phosphate rock was collected from Minjingu Phosphate mine, Arusha, Tanzania.

3.2 Soil sampling and sample preparation

Ten sub-samples from an area of half a hectare located in Tonga were collected randomly at a depth of 0-20 cm and mixed to constitute a representative sample. The composite sample was air-dried and ground to pass through an 8-mm sieve for pot experiment. A sub-sample was further ground to pass through a 2-mm and 0.5 mm sieve for laboratory analysis.

3.3 Pot experiment

The experiment was carried out during February to March 2002 in a glasshouse at Butare National University of Rwanda. Four kg of soil was weighed into clean five litre plastic pots. Thirty treatments involving; four levels of lime, two sources of green manures and one source of P as MPR in factorial combination were tested in a randomised block design and replicated three times. The treatments combinations are listed below:

1. Treatments 1-5, with lime application rates of 0, 0.25, 0.5, 0.75 and 1 unit of the liming requirement based on exchangeable Al: Equivalent to; 0, 0.6, 1.2, 1.8 and 2.4 g lime kg⁻¹ soil.
2. Treatments 6-10: each treatment listed in (1) + 50 mg P kg⁻¹ (as MPR)
3. Treatments 11-15: each treatment listed in (1) + 2.5 g Tephrosia kg⁻¹
4. Treatments 16-20: each treatment listed in (1) + 2.5 g Tithonia kg⁻¹
5. Treatments 21-25: each treatment listed in (2) + 2.5 g Tephrosia kg⁻¹
6. Treatments 26-30: each treatment listed in (2) + 2.5 g Tithonia kg⁻¹

The liming material used was a mixture of travertine and dolomite at a ratio of 1:1. The liming rates were calculated on the basis of partial or complete neutralization of exchangeable Al based on the Kamprath method where 1.5 cmol (+) of CaCO₃ was assumed to neutralise 1 cmol (+) exchangeable Al kg⁻¹. The green manures were Tithonia and Tephrosia fresh leaves. Appropriate quantities of each amendment were thoroughly mixed with the soil samples before filling the pots and sowing. The

treated soil samples were moistened to field capacity and incubated for two weeks. Six maize seeds were sown in each pot. Thinning was done to two plants in each pot one week after emergence. Plants were watered frequently before any signs of water stress has occurred, by adding sufficient deionised water to bring the water content to field capacity.

Plants were harvested after 42 days of growth. Shoots were cut at about one cm above the soil surface and were oven dried at 65° to constant weight and weighed. Then the samples were cut to small pieces and ground to pass through 0.5mm sieve and stored to await analysis.

3.4 Field experiment

A field experiment was conducted at Tonga cell in Ngoma District, Butare region, Rwanda during the October 2001 to February 2002 growing season. A soil profile was excavated and described and chemical analysis of soil samples from different horizons was made (Appendix 2). The soil was classified as Gleyic-Alumic Ferralsol (Hyper dystic) (FAO, 1999). The experimental site is located at 2°35'S and 29°43'E at an altitude of 1 734 m.a.s.l. Butare region has bimodal rainfall pattern with the long season starting from October to February (season A) and short season starting in March to June (season B). Land preparation included ploughing followed by harrowing. Then treatment plots of 5m x 6m were demarcated. The factors tested were limestone, MPR, TSP, green manures and the currently recommended rate of

fertilizer. Those inputs were spread on appropriate plots after randomisation and mixed with the soil using hand hoes.

For the treatment with the currently recommended fertilizer rate, burned lime and commercial NPK were used; for the other treatments the rates of organic or inorganic fertilisers were calculated as follows: (i) Rates of lime (mixture of travertine and dolomite) were calculated by Kamprath method (1.5 cmol (+) of CaCO_3 neutralising 1 cmol (+) kg^{-1} exchangeable Al). In this experiment, an amount equal to a half of that required for neutralizing exchangeable Al was used for all treatments. Exchangeable Al in the experimental soil was 3.4 cmol (+) kg^{-1} and half of the amount required to neutralize this level of exchangeable Al is 2 377 kg lime ha^{-1} . (ii) The rate of green manures was 5 t ha^{-1} on dry matter basis and the amounts of different nutrients associated with this rate of green manures are shown in Table 1. Phosphorus from MPR and TSP was applied at the rate of 100 kg ha^{-1} . A total of 13 treatments as listed below were tested and these were arranged in a completely randomised block design with three replications. The different treatments tested are listed below and quantities of nutrients added in the different treatments are presented in Table 1.

T1: Control

T2: MPR (100 kg P ha^{-1})

T3: Limestone 2 377 kg ha^{-1}

T4: Tithonia green manure (5 t ha^{-1})

T5: Tephrosia green manure (5 t ha^{-1})

T6: Tephrosia + MPR

T7: Tithonia +MPR

T8: Tithonia + Limestone

T9: Tephrosia + Limestone

T10: 175kg N ha⁻¹, 100 kg P ha⁻¹ as Urea and TSP, respectively +

Limestone (NPL)

T11: Tithonia + Limestone +MPR

T12: Tephrosia + Limestone +MPR

T13: Recommended rate of N, P, K and burned Lime (50 kg N, 22.5 kg P, 42.5 kg K and 2000kg lime).

The source of N, P and K was a compound fertilizer with a grade of 17% N, 17% P₂O₅ and 17% K₂O.

Table 1. Quantities of nutrients added in different treatments

Treatments	N	P	K (kg ha ⁻¹)	Ca	Mg
Control	0	0	0	0	0
MPR	0	100	7.3	253.1	15.8
Limestone	0	1.19	14.26	665.6	344.7
Tithonia	175	17.5	210.0	125.0	75.0
Tephrosia	125	12	100	100	70
Tephrosia + MPR	125	112	107.3	353.1	85.8
Tithonia + MPR	175.0	117.5	217.3	378.1	90.8
Tithonia + limestone	175	18.7	224.3	790.6	419.7
Tephrosia + limestone	125	13.19	114.3	775.6	414.7
NP + limestone	175	100	14.26	730.6	344.7
Tithonia+limes.+MPR	175	118.7	231.6	1043.7	435.5
Tephrosia+limest.+MPR	125	113.9	121.6	1018.7	430.5
NPKL	50	22.5	68.5	950.0	200.0

To minimize surface water movement and consequent losses of soil nutrients, bunds were made around each plot. Two seeds were sown per hole at a spacing of 50cm x 60 cm. Sowing was done two weeks after liming, green manuring and fertilizer application. Seedlings were then thinned to one plant per hill two weeks after emergence giving a plant population of 42 000 ha⁻¹. Inter-plot and inter-block spacing were one meter and two meters, respectively.

Frequent weeding was done to ensure the experimental plots were almost free of weeds for most of the plant growth period. Stalk borer attack on maize was observed after two months and was controlled by chemical means using Sumicombi pesticide.

Maize was harvested after 150 days of growth. A guard row was left around each plot so that only the inner 5 rows were harvested. Cobs were harvested and shelled and the grains were sun dried, winnowed and weighed. Grain yield was calculated at 13% moisture content and reported in kg ha⁻¹.

The climatic data during the growing season (October 2001-March 2002) is summarised in Appendix 3. The total rainfall during the growing season was 1 302 mm. High amounts of rainfall were observed in November, January and April while the months of December and February had the lowest rainfall. The mean annual temperature ranged between 18.7-21.7°C. The mean maxima and the mean minima temperature ranged between 23.8-25.3°C and 13.0-18.0°C, respectively.

3.5 Soil sampling from pot and field experiments

Soil samples from the pot experiment were collected after harvesting (42 days after planting) from each pot for laboratory analysis. In the field experiment, ten sub samples were collected randomly from each plot to a depth of 15cm. Sampling was done after harvesting using a soil auger.

3.6 Plant sampling

For the estimation of nutrient concentration in maize plants in the field, fifteen leaves were sampled randomly from each plot at approximately 50% tasselling stage. In the glasshouse experiment, maize shoots from each pot were harvested at 42 days after emergence. These samples were oven-dried at 65°C to constant weight, chopped and ground to pass through a 0.5mm sieve and stored to await analysis.

3.7 Laboratory analysis

3.7.1 Soil analysis

Particle size analysis was done by the hydrometer method (Gee and Bauder, 1986), and textural classes were determined using the USDA textural class triangle. Soil pH was determined using a pH meter in 1:2.5 soil: water and KCl suspensions (Page *et al.*, 1982). Cation exchangeable capacity was determined by the ammonium acetate saturation method (Rhoades, 1982). Exchangeable Ca and Mg in the ammonium acetate leachate were determined by atomic absorption spectrophotometer. Exchangeable K was determined by using a flame spectrophotometer and Al + H was

determined by atomic absorption spectrophotometry. Organic carbon was determined by the Walkey and Black method (Page *et al.*, 1982). Total N was determined by semi-micro Kjeldahl procedure (Page *et al.*, 1982). Available P was extracted by Bray1 method (Page *et al.*, 1982) and determined colorimetrically using the ascorbic acid method (IITA, 1979). Total P was extracted by dry ashing procedure described by Moberg (2000). Total P was determined using the ascorbic acid molybdate blue reagent using a spectrophotometer at a wavelength of 884nm.

3.7.2 Plant analysis

Plant materials was digested in a mixture of HNO_3 and H_2O_2 as outlined by Jones and Case (1990) and modified by Moberg (2000). The modifications were: instead of 2 g, 0.5 g of dried plant samples ground to pass through a 0.5 mm sieve were weighed and put into digestion tubes. Then 5 ml of 68% HNO_3 was added into each tube, and the mixture was left to stand overnight. The tubes were then placed in a digestion block at 125°C for one-hour to digest before they were taken off and cooled. Then 5 ml H_2O_2 were added into each tube and the contents heated at 70°C on the digestion block until the reaction stopped. This treatment was repeated until the digest was colourless or nearly colourless. The digest was then heated on the digestion block at 180°C to almost dryness. After cooling 10 ml of 10% HNO_3 was added and the dissolved digest was transferred quantitatively to a 100 ml volumetric flask before being filled to the mark with distilled water. The content of P in the digest was determined using the ascorbic acid-molybdate blue method. Ca, Mg, Zn and Cu from the digests were determined by atomic absorption spectrophotometry

while K concentration was determined by flame spectrophotometry. Analysis of total N was done following the procedure given for total N in section 3.7.1

3.8 Data processing

Analysis of variance (ANOVA) for the data was done and means were compared using Duncan's Multiple Range Test (DMRT). Regression and coefficient of correlation (r) between soil properties and plant growth and limestone application rates with and without PR, green manures (Tephrosia and Tithonia) for greenhouse trials were calculated. The following model was used for the regression equations,

$$Y_i = A_0 + Bx_i + C_i,$$

Where, Y_i the dependent variable refers to soil and plant growth parameters such as soil pHw, DM yield, plant P content, plant N content, plant Ca contents and plant Mg content.

X_i is an input variable (limestone applications rates with and without MPR, GM).

A is the Y-intercept for the regression line.

B is the regression coefficient.

C_i is to the random error.

The relationship between limestone with and without PR, Tithonia or Tephrosia GM on plant and soil content of N, P, K, Ca, and Mg in greenhouse were established. The SAS programme was used for statistical analysis and Excel software was used for data management and for fitting data into different relationships.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Experimental soil

Soil physical and chemical properties in the area of the study are summarized in Table 2: The textural class of the soil was sandy clay loam. The pH in water was 4.7, which would be ranked as low according to Landon (1996). The Al saturation was 65%, which would be rated as medium according to Landon (1996). The CEC value was 5.2; which would be rated as low according to Landon (1996). Exchangeable Ca, Mg, K would all be ranked as low according to Landon (1996) with K being the lowest and most likely to be severely limiting to crop production. Organic carbon and N values were 2.0% and 0.11%, respectively, which would both be ranked as low according to Landon (1996). The Bray 1 P value was 5 mg kg⁻¹; which would be rated as low according to Landon (1996).

**Table 2. Some physical and chemical properties of the soil of the study site at
Tonga, Butare, Rwanda**

Property	Content
1. Soil physical properties	
Particle sizes	
Sand (%)	54.4
Silt (%)	16
Clay (%)	29.6
Soil texture	Sandy clay loam
2. Soil chemical properties	
pH in water (1:2.5 soil water ratio)	4.7
pH in KCl (1:2.5 soil KCl ratio)	4.0
Exchangeable acidity (cmol (+) kg ⁻¹)	4.1
Exchangeable Al ³⁺ (cmol (+) kg ⁻¹)	3.4
Exchangeable H ⁺ (cmol (+) kg ⁻¹)	0.7
Al saturation (%)	65.4
Exchangeable bases (cmol (+) kg ⁻¹)	
Ca ²⁺	0.8
Mg ²⁺	0.2
K ⁺	0.09
Na ⁺	0.04
CEC (cmol (+) kg ⁻¹)	5.2
Base saturation (%)	21.7
Organic carbon (%)	2.0
Total N (%)	0.11
Bray 1 P (mg kg ⁻¹)	5
Total P (mg kg ⁻¹)	270

4.2 Chemical characteristics of MPR, lime and TSP used in the experiment

The chemical characteristics of MPR, liming materials and TSP are summarised in Table 3. The Ca/Mg ratio of the dolomite and travertine mixture was 1.93, which is ranked as very low by Beenart (1999). The burned lime had normal range of Ca/Mg ratio (4.8). The total P_2O_5 content of MPR was 28.8% while the P_2O_5 soluble in NAC (neutral ammonium acetate) was 5.6%. The later parameter had been suggested by Lehr and McClellan (1972) to be a measure of PR solubility and thus a guide for PR selection. Leon *et al.* (1986) categorised PRs based on their solubility in different solvents. Phosphate rocks with NAC soluble P between 2.4-2.9% were ranked as having high relative agronomic potential (RAP). Table 3 shows that the NAC soluble P_2O_5 for MPR was 5.6% equivalent to 2.5% P. Thus, MPR would be categorised as having high relative agronomic potential.

Table 3. Initial chemical properties of the experimental materials (MPR, the mixture of travertine and dolomite and TSP)

Chemical properties	Experimental materials			
	MPR*	Travertine+Dolomite	Burned lime	TSP
Total P (%)	12.8	0.05	-	20
NAC ¹ P (%)	2.5		-	
Calcium (Ca) (%)	32.9	28.0	47.5	13
Magnesium (Mg) (%)	2.2	14.5	10	
Potassium (K) (%)	1.0	0.6	1.3	

*: Source: Harris (1981)

1: Neutral ammonium citrate

4.3 Organic materials

Tithonia leaves were of higher resource quality than Tephrosia leaves based on their chemical characteristics presented in Table 4. The N concentrations of the leaves of both materials were higher than the critical level of 2% to 2.5% below which point net N immobilisation from the soil would be expected (Gachengo *et al.*, 1999). The P concentration of Tephrosia leaves however, was below the critical level of 0.25% and P immobilisation would be expected (Blair and Boland, 1978; Palm *et al.*, 1997; Gachengo *et al.* 1999). The C/N ratios were 10% and 22% for Tithonia and Tephrosia, respectively. Jama (2000) reported lignin content in Tithonia to be 6.5% and extractable polyphenols concentrations of 1.6%, which are below levels that significantly reduce decomposition (Palm and Rowland, 1997). The reported levels of lignin and polyphenols in Tephrosia green biomass are 8.0-8.3% and 2.37%, respectively (TSBF, 1999). Based on the quoted levels of lignin and polyphenols of the two green manures materials, Tithonia would be expected to decompose faster than Tephrosia. The K concentration of Tithonia leaves is double comparatively to Tephrosia. Tithonia and Tephrosia have almost the same content of Ca and Mg content in their leaves.

Table 4. Some chemical properties of green manures used in the experiments

	OC	N	P	K	Mg	Ca	C/N
	(%)						
Tithonia	35	3.5	0.35	4.2	1.5	2.5	10
Tephrosia	55	2.5	0.24	2.0	1.4	2.0	22

4.4 Greenhouse experiment

In this study, limestone means a mixture of travertine and dolomite in 1:1 ratio.

4.4.1 Effects of treatments on dry matter yield, concentrations of nutrients in plants and uptake

Data showing the effects of limestone, green manures, MPR and their combinations on dry matter yield and nutrient uptake are presented in Appendix 2. Selected regression equations and coefficients of correlation (r) between dry matter yield, nutrient uptake and limestone application rates with and without MPR and GM are presented in Table 5. The means of the effects of limestone, MPR and GM on concentrations of different nutrients in maize shoots are presented in Table 6.

4.4.1.1 Effects of limestone, MPR, GM and their combination on dry matter yield

Effects of limestone, MPR and GM on dry matter yield are presented in Figure 1. Generally, there were positive correlations (Table 5) between DM yield and limestone rates when limestone was applied alone, with MPR and with Tithonia and Tephrosia ($r = 0.89$, $r = 0.96$, $r = 0.67$ and $r = 0.92$ respectively), while limestone applied together with MPR and green manures gave significant negative correlations ($r = -0.89$ and $r = -0.85$ respectively for Tithonia + MPR + limestone and Tephrosia + limestone + MPR treatments).

Table 5. Selected regressions equations and correlation coefficient (r) for relationships between plant growth and nutrients uptake as influenced by the application of different amendment

Parameters	Limestone	MPR + limestone	Tithonia + limestone	Tephrosia + limestone	Tith.+limest.+ MPR	Teph.+limest.+ MPR
DM yield	$y = 0.91x + 1.69$ $r = 0.95$	$y = 0.25x + 4.18$ $r = 0.96$	$y = 0.51x + 4.41$ $r = 0.66$	$y = 1.49x + 2.61$ $r = 0.92$	$Y = -2.48x + 8.27$ $r = -0.89$	$Y = -2.01x + 6.65$ $R = -0.72$
N	$y = 33.73x + 29$ $r = 0.92$	$y = 16.29x + 57.4$ $r = 0.65$	$y = 22.3x + 122.7$ $r = 0.84$	$y = 45.36x + 65.37$ $r = 0.89$	$y = -40.93x + 199.4$ $r = -0.58$	$y = -46.09x + 142.7$ $r = -0.95$
Ca	$y = 14.35x + 11.64$ $r = 0.95$	$y = 5.06x + 30.49$ $r = 0.65$	$y = 2.18x + 31.63$ $r = 0.28$	$y = 19.53x + 19.68$ $r = 0.93$	$y = -16.94x + 67.65$ $r = -0.77$	$y = -11.41x + 49.1$ $r = -0.52$
Mg	$y = 3.05x + 0.63$ $r = 0.95$	$y = 1.57x + 11.5$ $r = 0.96$	$y = 2.3x + 12.8$ $r = 0.91$	$y = 3.2x + 7.31$ $r = 0.89$	$y = -x + 33.2$ $r = -0.65$	$y = -0.12x + 23.4$ $r = -0.077$
P	$y = 1.45x + 2.21$ $r = 0.84$	$y = 2.18x + 5.56$ $r = 0.96$	$y = 0.99x + 6.95$ $r = 0.88$	$y = 1.99x + 3.76$ $r = 80$	$y = -5.14x + 16.69$ $r = -0.81$	$y = -3.46x + 11.07$ $r = -0.86$
K	$y = 2.67x + 24.59$ $r = 0.89$	$y = 0.51x + 59.99$ $r = 0.25$	$y = 2.6x + 62.34$ $r = 0.57$	$y = 5.15x + 33.79$ $r = 0.92$	$y = -6.67x + 127.9$ $r = -0.84$	$y = -8.17x + 103.13$ $r = -0.88$

Addition of green manures (Tithonia and Tephrosia) alone improved DM yield in all treatments, but in the treatments with the three amendments (limestone, MPR and green manures) yield depression was observed at high rates of limestone i.e. the highest DM yield was associated with the lowest limestone rate (equivalent to a quarter of the lime requirement) followed by a decrease in yield at higher rates of limestone. Tithonia + limestone + MPR at the lowest rate of limestone gave the highest DM yield but higher limestone rates decreased DM yield. MPR + limestone and Tithonia + limestone occupied intermediate position in influencing DM yield. Limestone alone had the smallest DM yield.

These results indicate that the test soil has multiple nutrients deficiencies, which are alleviated appreciably by a combination of amendments. For instance a combination of MPR, GMs and limestone would supply ample amounts of N, P, Ca and these nutrients must have contributed to the high yields from these treatments. However, high rates of limestone decreased yields probably because of unfavourable interaction with other nutrients. This aspect will be examined further in subsequent sections. The fact that MPR gave higher yield than limestone alone suggest that P is more limiting than Ca and/or Al toxicity is not a serious problem at least in the short run.

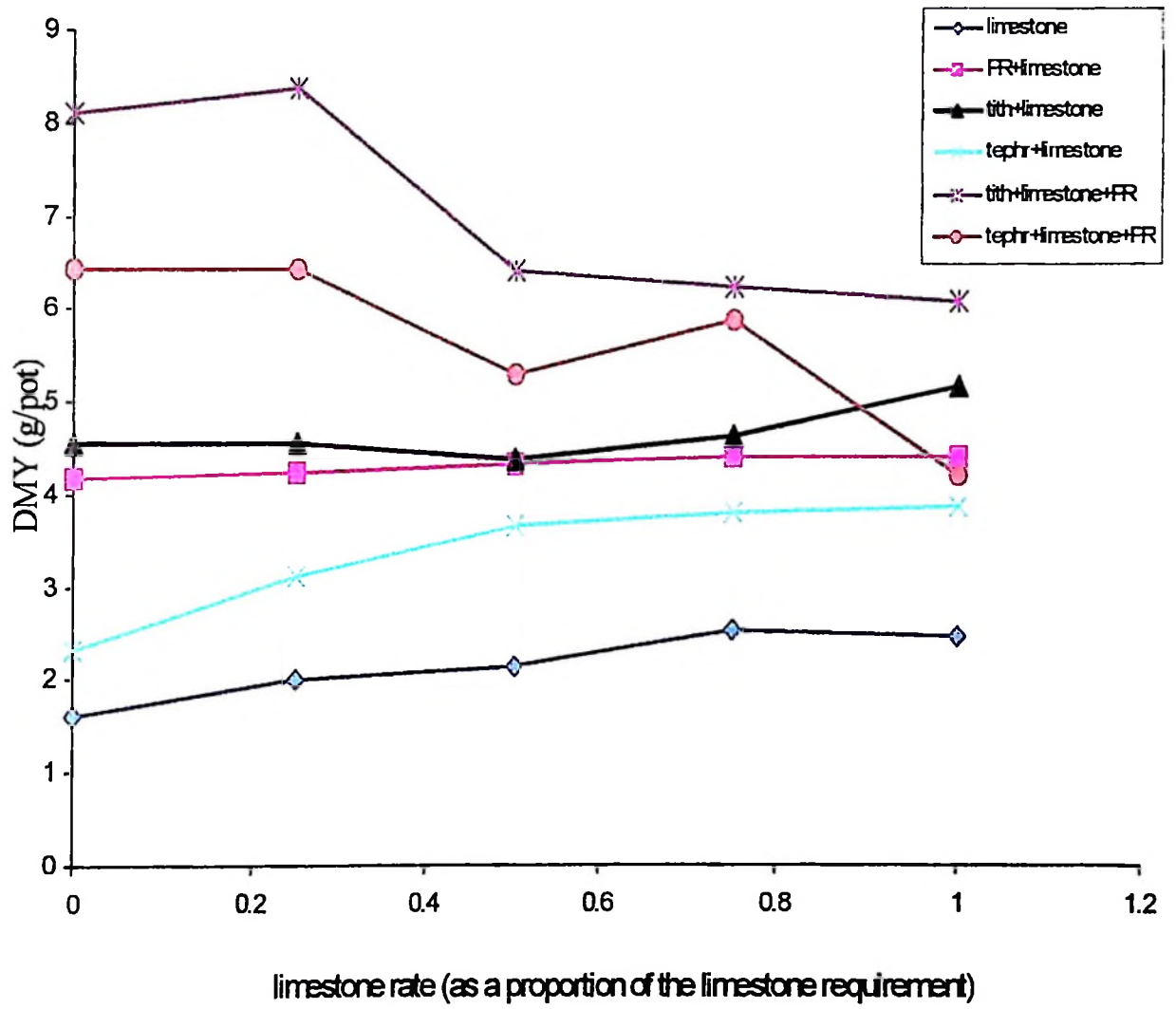


Figure 1. Effects of limestone, MPR, GM and their combination on maize dry matter yield

Table 6. Effects of limestone, MPR and GM on concentrations of different nutrients in maize shoots

6a. Effects of different levels of limestone on nutrients concentrations

	N	P	K	Ca	Mg	Zn
	(%)					mg kg ⁻¹
L0	1.4b	0.12b	1.60a	0.64c	0.29e	41.6a
L1	2.1a	0.13b	1.53ab	0.80b	0.36d	23.9b
L2	2.2a	0.15a	1.57ab	0.89ab	0.43c	17.0b
L3	2.4a	0.14a	1.50ab	0.98a	0.46a	20.7b
L4	2.4a	0.13b	1.43b	0.97a	0.44b	19.2b
CV %	11.5	4.0	5.2	5.9	2.8	24.1

Any two means in the same column not followed by the same letter are significantly different at $P = 0.05$

6b. Effects of a combination Tithonia green manure and limestone on nutrients concentrations

	N	P	K	Ca	Mg	Zn
	(%)					mg kg ⁻¹
L0	1.4b	0.12b	1.60	0.64c	0.29c	41.6a
L0 Tithonia	2.73a	0.15a	1.47	0.69bc	0.30c	41.7a
L1 Tithonia	2.90a	0.15a	1.56	0.78a	0.44b	37.13ab
L2 Tithonia	2.90a	0.16a	1.60	0.66bc	0.45b	29.7bc
L3 Tithonia	2.90a	0.16a	1.37	0.68bc	0.45b	28.3bc
L4 Tithonia	2.93a	0.15a	1.60	0.70b	0.48a	27.1c
CV %	8.3	4.6	10.0	3.6	2.7	13.8

Any two means in the same column not followed by the same letter are significantly different at $P = 0.05$

6c. Effects of a combination Tephrosia green manure and limestone on nutrients concentrations

	N	P	K	Ca	Mg	Zn
	(%)					mg kg ⁻¹
L0	1.4b	0.12c	1.33	0.64d	0.29c	42.9a
L0 Tephrosia	2.4a	0.14ab	1.5	0.71cd	0.36c	38.0ab
L1 Tephrosia	2.6a	0.14ab	1.5	0.82bc	0.44b	26.4bc
L2 Tephrosia	2.7a	0.14ab	1.5	0.89ab	0.54a	27.3bc
L3 Tephrosia	2.7a	0.16a	1.5	0.93a	0.57a	19.6c
L4 Tephrosia	2.6a	0.13bc	1.6	0.96a	0.57a	17.0
CV %	7.0	8.3	9.1	7.2	8.6	24.8

Any two means in the same column not followed by the same letter are significantly different at $P = 0.05$

6d. Effects of a combination MPR and limestone on nutrients concentrations

	N	P	K	Ca	Mg	Zn
	(%)					mg kg ⁻¹
L0	1.2c	0.12c	1.6	0.64c	0.29b	41.6a
L0 MPR	1.4bc	0.13bc	1.3	0.76b	0.32b	35.4a
L1 MPR	1.7ab	0.14b	1.4	0.71bc	0.33b	23.0b
L2 MPR	1.5abc	0.15b	1.4	0.72b	0.38a	20.8b
L3 MPR	1.7a	0.17a	1.2	0.86a	0.43a	20.7a
L4 MPR	1.5ab	0.17a	1.4	0.78	0.43a	22.2a
CV %	9.7	6.6	11.5	5.1	6.6	22.8

Any two means in the same column not followed by the same letter are significantly different at $P = 0.05$

6e. Effects of a combination Tithonia green manure, MPR and limestone on nutrients concentrations

	N	P	K	Ca	Mg	Zn
	(%)					mg kg ⁻¹
L0	1.4c	0.12b	1.6	0.64d	0.29d	41.6a
L0 Tithonia MPR	2.2b	0.19a	1.4	0.78c	0.38c	21.3b
L1 Tithonia MPR	2.7a	0.21a	1.5	0.86ab	0.41b	40.4a
L2 Tithonia MPR	2.7a	0.21a	1.6	0.88a	0.47a	18.9b
L3 Tithonia MPR	2.6a	0.19a	1.6	0.81bc	0.46a	30.2ab
L4 Tithonia MPR	2.6a	0.20a	1.6	0.87ab	0.47a	28.9ab
CV %	8.6	9.2	5.9	4.0	3.6	27.6

Any two means in the same column not followed by the same letter are significantly different at $P = 0.05$

6f. Effects of a combination Tephrosia green manure, MPR and limestone on nutrients concentrations

	N	P	K	Ca	Mg	Zn
	(%)					mg kg ⁻¹
L0	1.4b	0.12c	1.6	0.64b	0.29d	41.6
L0 Tephrosia MPR	2.2a	0.16b	1.4	0.68b	0.33c	16.4
L1 Tephrosia MPR	2.1a	0.16b	1.5	0.79a	0.37b	49.1
L2 Tephrosia MPR	2.1a	0.20a	1.3	0.81a	0.48a	26.0
L3 Tephrosia MPR	1.9ab	0.15b	1.2	0.86a	0.44a	44.1
L4 Tephrosia MPR	2.3a	0.16b	1.5	0.70b	0.46a	16.8
CV %	13.8	7.6	12.8	6.1	4.9	45.9

Any two means in the same column not followed by the same letter are significantly different at $P = 0.05$

4.4.1.2 Effects of limestone, MPR and GM on N and P concentrations and uptake in the greenhouse experiment

Nitrogen concentrations in maize shoots ranged from 1.2 – 2.9%. Chapman (1965) set the following ranges of N content of plants N values of < 1.8% are ranked as deficient and those between 1.8 – 3.5% are ranked as low, while those > 3.5% are ranked as adequate for maize plants sampled at 30 – 40 days after planting. Except the control, which contained deficient N, the other treatments were low in N content. However, the GM treatments were associated with relatively high N concentrations in this study which ranged from 2.4 – 2.9% and were close to the sufficiency level.

Figures 2 and 3 show the effect of limestone, MPR, GM and their combinations on N and P uptake respectively. Generally, there were positive correlations (Table 5) between N and limestone rates when limestone was applied alone, or in combination with MPR, Tithonia or Tephrosia ($r = 0.92$, $r = 0.65$, $r = 0.84$ and $r = 0.9$, respectively). However when limestone was applied in combination with MPR and green manures negative correlations ($r = - 0.58$ and $r = - 0.95$, respectively) were found for Tithonia + MPR + limestone and Tephrosia + limestone + MPR treatments.

Addition of green manures (Tithonia and Tephrosia) improved N in all treatments. In the treatments combining limestone, MPR and green manures N was depressed at high rates of limestone. Tithonia green manure caused higher N uptake than Tephrosia. This could be due to both higher concentration of N and faster decomposition of Tithonia leaves than of Tephrosia leaves.

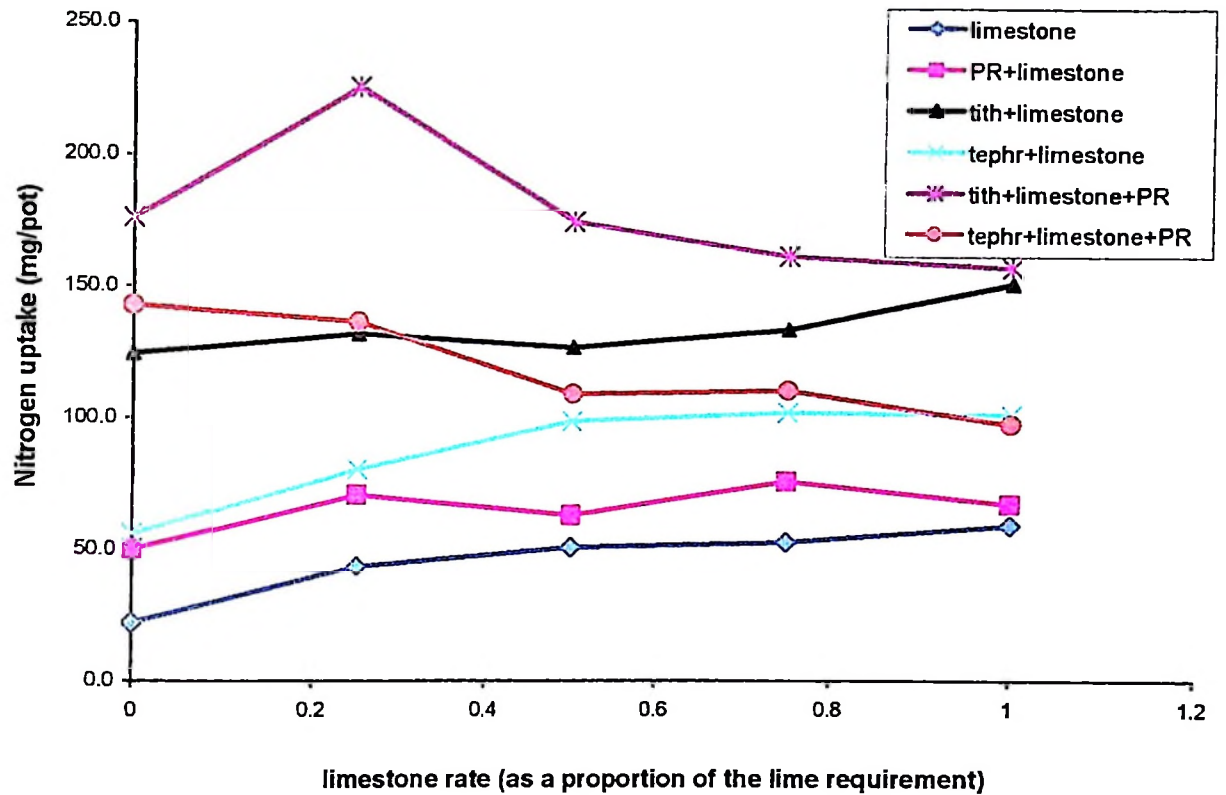


Figure 2. Effects of limestone, MPR, GM and their combination on N uptake
in the greenhouse experiment

Liming significantly increased N uptake indicating stimulation of soil organic N mineralisation by soil microorganisms while in the mixtures of green manures and limestone there was also a larger amount of readily mineralisable N. A similar observation was noted by Manguial (1997) whereby at two weeks after *Sesbanium rostrata* green manure incorporation (95 days after lime application), liming increased N availability by 2.4 times above the control (no lime).

The results for P concentration as influenced by different treatments are presented in Table 6. Phosphorus concentrations in maize shoots ranged from 0.12 – 0.21%. The P concentration values achieved were below the sufficiency range of 0.25 – 0.4% reported by Jones and Eck (1973). This means that higher rates of P are required to achieve sufficient levels. However a combination of limestone, MPR and Tithonia was associated with the highest P concentrations in this study which ranged from 0.19 – 0.21% and were close to the sufficiency level. These treatments were also associated with the highest P uptake. This indicates that this combination was favourable to P availability.

There were positive correlations (Table 5) between P concentration and limestone rates when limestone was applied alone, with MPR and/or in combination with Tithonia or Tephrosia ($r = 0.84$, $r = 0.96$, $r = 0.88$ and $r = 0.8$, respectively). However, when limestone was applied in combination with MPR and green manures negative correlations ($r = -0.8$ and $r = -0.86$, respectively) were found for Tithonia + MPR + limestone and Tephrosia + limestone + MPR treatments.

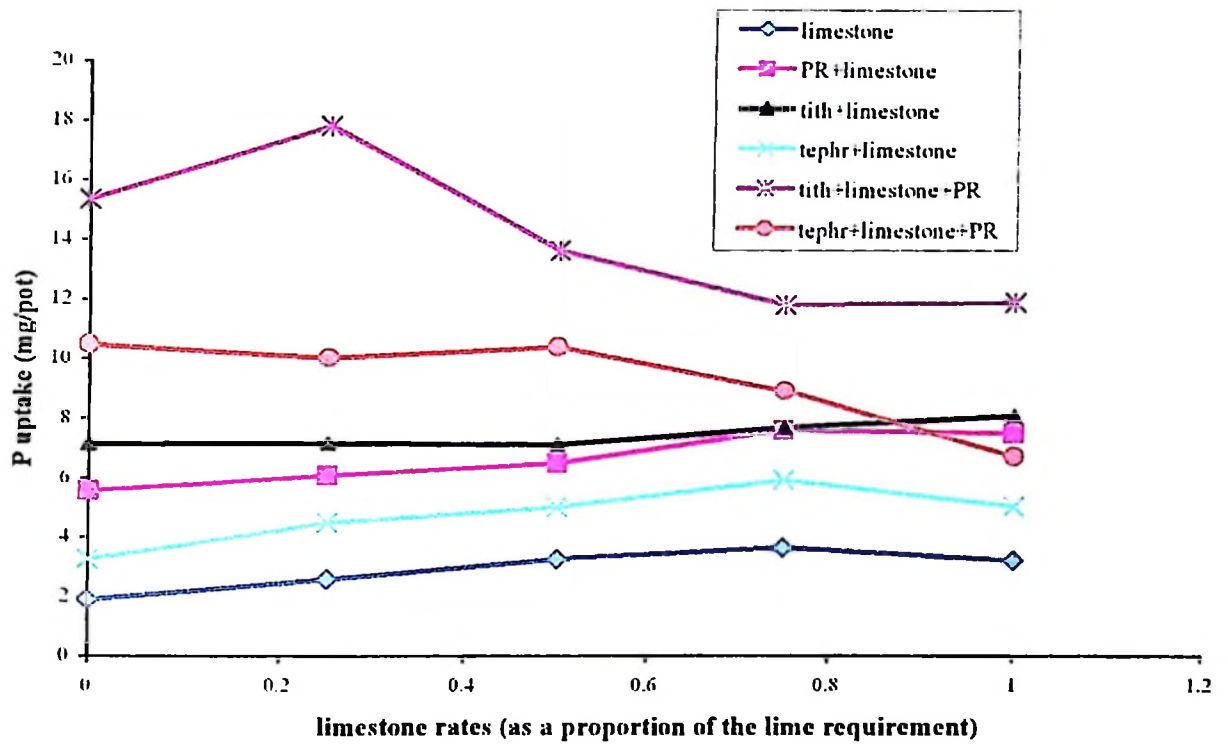


Figure 3. Effects of limestone, MPR, GM and their combination on P uptake in the greenhouse experiment

Addition of green manures (Tithonia and Tephrosia) improved P uptake in all treatments. In the treatments combining limestone, MPR and green manures P uptake was depressed at high rates of limestone. The limestone + MPR and Tithonia + limestone treatments had similar effects on P uptake. The lowest P uptake was observed in treatments with limestone alone.

Application of Tithonia GM resulted in higher P uptake than Tephrosia GM and the superiority was maintained even at high rates of limestone. This could be due to the P concentration in Tithonia, which was higher (0.35%) than the critical level of 0.25% for net P mineralisation (Jama *et al.*, 2000) while the P concentration of Tephrosia was at the threshold level (0.24%). Thus, Tithonia biomass might have decomposed faster than Tephrosia and released P; which might have also decreased P adsorption more than Tephrosia. The decrease in P uptake when the three amendments were applied at high rate of limestone was probably caused by a decrease in PR dissolution. But MPR still maintained higher P levels than the control, which supported moderately high DM yield even when limestone was applied at high rate.

The extent of root growth may be the main factor for the slight increase in P uptake in the mixture of limestone and MPR treatments and limestone alone. Limestone increased pH and alleviated aluminium toxicity. The data (Appendix 1 and Appendix 2) show that the pH effect on P uptake by plants was more positively marked in the

mixture of limestone and MPR treatments, however the amount of Bray 1 P in the same treatments decreased with increasing limestone rate.

4.4.1.3 Effects of limestone, MPR, GM and their combination on K concentrations and uptake

The K concentration ranged from 1.2 – 1.6%. According to Tandon (1995) maize plant is said to have sufficient K if concentration is in the range of 2.5 – 4.0%. The results indicate that all K levels were in the deficiency range.

Correlations between K uptake and the different treatments are given in Table 5. There were positive correlations between K uptake when limestone was applied alone or in combination with Tithonia or Tephrosia ($r = 0.89$, $r = 0.56$ and $r = 0.91$, respectively). However, weak correlation ($r = 0.24$) was noted when limestone was applied in combination with MPR. When limestone was applied in combination with MPR and green manures negative correlations ($r = - 0.84$, $r = - 0.88$, respectively) were found for Tithonia + MPR + limestone and Tephrosia + limestone + MPR treatments.

Figure 4 shows the effects of limestone, MPR, GM and their combinations on K uptake. In treatments combining limestone, MPR and green manures, K uptake was high but was depressed at high rates of limestone. The lowest K uptake was observed in the treatments with limestone alone followed by the Tephrosia + limestone

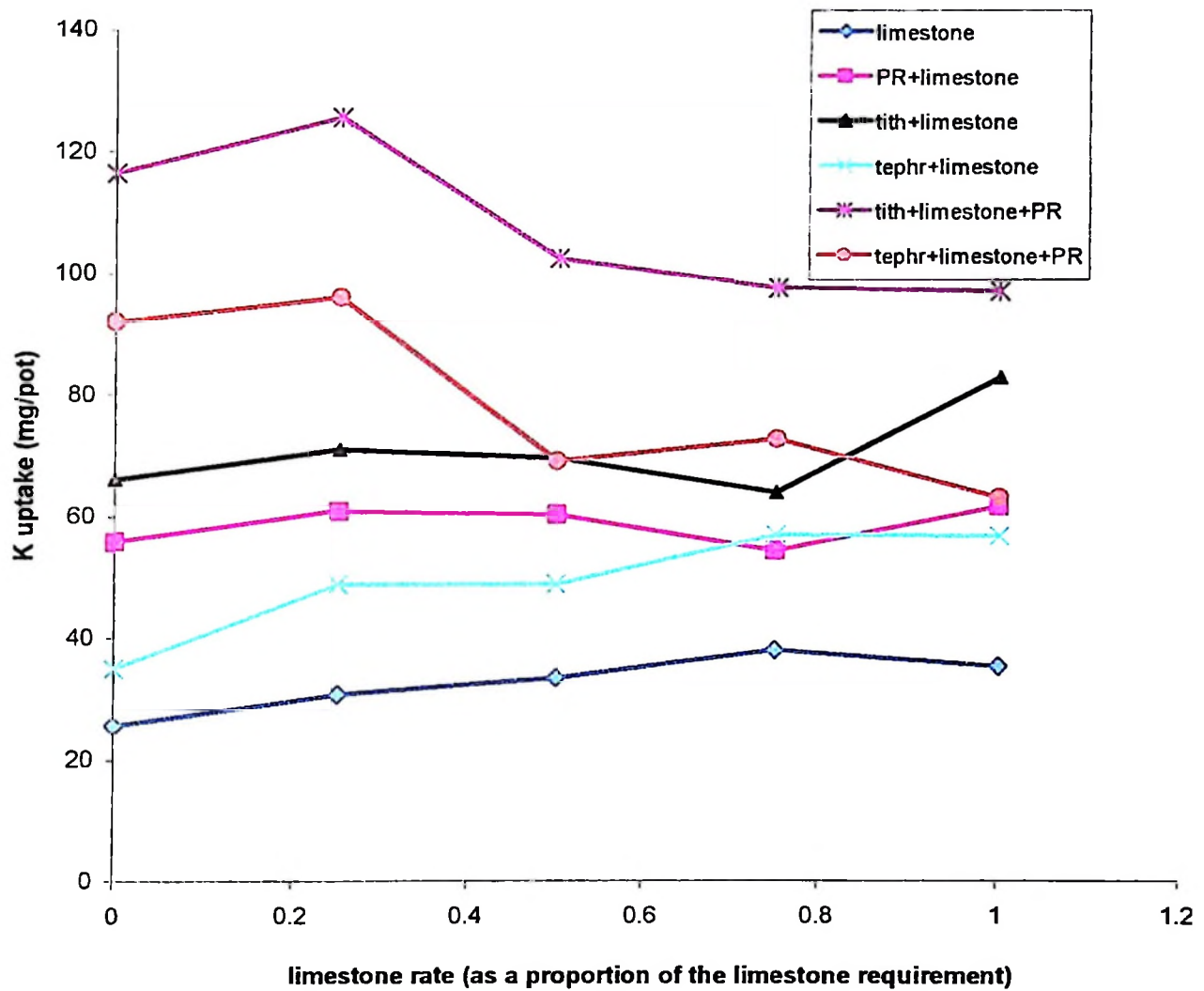


Figure 4. Effects of limestone, MPR, GM and their combination on K uptake in the greenhouse experiment

treatments and PR + limestone, while Tithonia + limestone occupied intermediate position in K uptake. Tithonia green manure caused higher K uptake than Tephrosia green manure. This could be due to the higher K content in Tithonia (4%) than in Tephrosia (2%) and the faster decomposition rate of Tithonia than Tephrosia. Tithonia green manure contains as much K as N (Table 4). Tithonia biomass improved K supply and thereby alleviated K deficiency. In an experiment in Western Kenya, maize yield was markedly higher with Tithonia biomass than with urea applied at an equivalent rate of 60 kg N ha⁻¹ when averaged for four P fertilizer treatments in which maize was not limited by P (ICRAF, 1998). The better performance of Tithonia biomass was due to addition of K supply.

4.4.3.4 Effects of limestone, MPR, GM and their combination on Ca and Mg concentrations and uptake

The Ca concentration ranged from 0.64 – 0.97% and all these values fall in the sufficiency range. This conclusion is based on the critical level of Ca in plants of 0.21 – 1.00% reported by Jones and Eck (1973). The Mg concentration ranged from 0.29 – 0.57%, which was in sufficient to high level according to the rating by Tandon (1995) who reported the critical range to be 0.15 – 0.45%.

Figures 5 and 6 show the effect of limestone, MPR and GM on Ca and Mg uptake, respectively. Generally, there were positive correlations (Table 5) between Ca and Mg uptake and limestone rates when limestone was applied alone or in combination

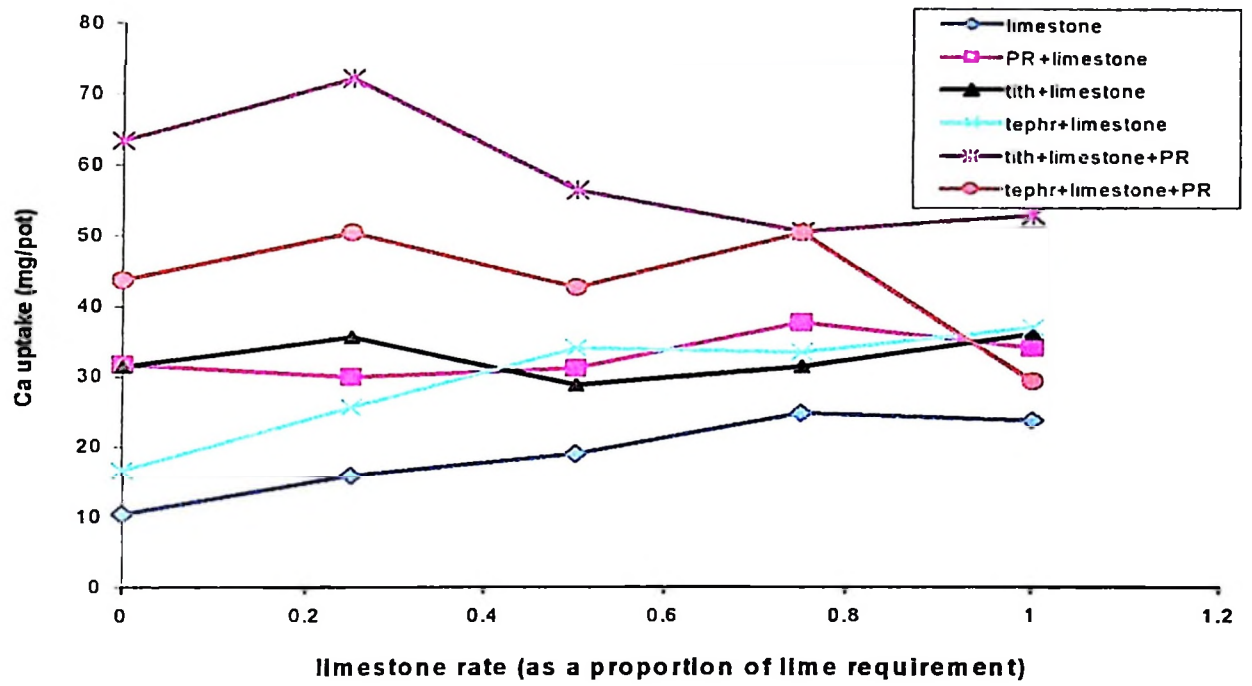


Figure 5. Effects of limestone, MPR, GM and their combination on Ca uptake in the greenhouse experiment

with MPR, Tithonia or Tephrosia (for Ca $r = 0.95$, $r = 0.65$, $r = 0.28$ and $r = 0.93$, respectively; for Mg the corresponding correlation coefficients were 0.99 , 0.97 , 0.91 and $r = 0.89$, respectively). However when limestone was applied in combination with MPR and green manures negative correlations (for Ca $r = -0.77$ and $r = -0.52$, respectively; for Mg $r = -0.64$, $r = -0.075$, respectively) were found for Tithonia + MPR + limestone and Tephrosia + limestone + MPR treatments.

Addition of green manures (Tithonia and Tephrosia) improved Ca and Mg in all treatments. In the treatments combining limestone, MPR and green manures, Ca and Mg uptake were depressed at high rates of limestone. This was consistent with the trend of DM yield. When there is a negative effect on growth in general, the consequence was low uptake of other nutrients even those, which were high in the soil solution.

In the treatments with the three amendments (limestone, MPR and green manures) Ca, Mg and K depression was observed for high rate of limestone i.e. there was an increase in Ca for the treatment with 0.25 of the lime requirement followed by decreases in Ca in the treatments with Tithonia. On the other hand, for the treatments with Tephrosia there was first an increase and then a decrease in Ca; for Mg there was an increase up to the rate of 0.75 of the lime requirement followed by decreases, and for K there was no change with 0.25 of the lime requirement followed by decreases with higher limestone rates. Tithonia gave higher Ca, Mg and K than

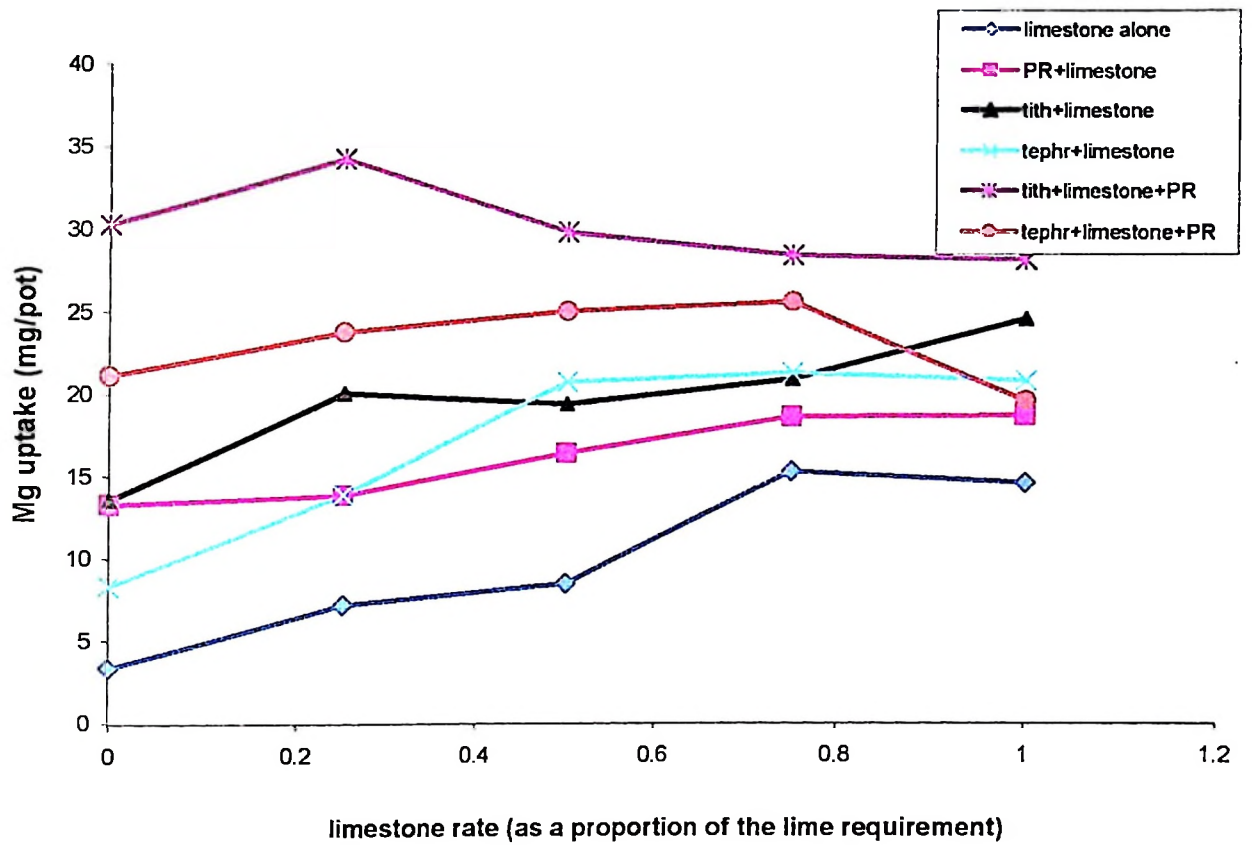


Figure 6. Effects of limestone, MPR, GM and their combination on Mg uptake in the greenhouse experiment

Tephrosia. Indeed, plant Ca, Mg and K contents for the Tithonia + limestone treatment was higher than for the Tephrosia + limestone +MPR treatment. When adding GM and MPR on limestone, which is rich in Ca, Mg and K, it is possible that high rates of limestone might have caused imbalance of other nutrients hence decreased their uptake.

4.4.1.5 Effects of limestone, MPR, GM and their combination on Zn uptake

The concentration of Zn in shoots ranged from 16.8 – 41.6%. Zn concentration values $< 20 \text{ mg kg}^{-1}$ are ranked as low and those between 20 – 60 mg kg^{-1} are ranked as sufficient for maize growth according to Tandon (1995). Thus the data in Table 6 indicate Zn levels in plants were in most cases adequate except in a few treatments combining the high rate of limestone and Tephrosia, Tephrosia + MPR, or high rate of limestone + Tephrosia + MPR.

4.4.2 Effects of limestone, MPR, GM and their combination on soil properties

The effects of limestone, green manures and MPR on selected properties in soil samples from the greenhouse experiment after harvesting maize shoots are presented in Appendix 1. Selected regression equations and correlation coefficients (r) between soil properties and limestone application rates with and without MPR and/or GM are presented in Table 7.

4.4.2.1 Effects of limestone, MPR, GM and their combination on soil pH

Liming increased pH in water and in KCl from 5.0 to 5.7 and 4.1 to 4.7, respectively. The highest pH in water was 5.7, which was associated with the lime rate sufficient to neutralise exchangeable Al, which would be rated as medium (Landon 1996).

Figure 7 shows the effect of limestone, MPR and GM on pH in water. There was a positive correlation between pH and limestone alone ($r = 0.98$), MPR + limestone ($r = 0.99$), Tephrosia + limestone ($r = 0.98$), Tithonia + limestone + MPR ($r = 0.95$) and Tephrosia + limestone + MPR ($r = 0.99$) (Table 7).

Table 7. Selected regression equations and coefficients of correlation (r) for relationship between soil properties as influenced by the application of different amendments

Parameters	Limest.	MPR + Limest.	Tithonia + limest.	Tephrosia + limest.	Tith. + limes.+MPR	Teph.+ limes.+MPR
W pH	$y = 0.6x + 5.11$ $r = 0.98$	$y = 0.57x + 5.15$ $r = 0.99$	$y = 0.55x + 4.94$ $r = 0.98$	$y = 0.6x + 4.99$ $r = 0.98$	$y = 0.51x + 5.15$ $r = 0.95$	$y = 0.53x + 5.17$ $r = 0.98$
Aluminium	$y = -2.24x + 2.74$ $r = 0.98$	$y = -1.88x + 2.31$ $r = 0.99$	$y = -2.48x + 2.77$ $r = 0.98$	$y = -2.52x + 2.87$ $r = 0.96$	$y = -1.46x + 2.3$ $r = 0.96$	$y = -1.92x + 2.67$ $r = 0.95$
Bray 1 P	$y = 2.02x + 9.51$ $r = 0.90$	$y = -10.33x + 23.6$ $r = 0.97$	$y = 2.3x + 11.19$ $r = 0.86$	$y = 1.08x + 10.2$ $r = 0.94$	$y = -12.79x + 30.26$ $r = 0.95$	$y = -13.61x + 27$ $r = 0.98$
Calcium	$y = 2.67x + 0.89$ $r = 0.98$	$y = 1.52x + 1.69$ $r = 0.96$	$y = 2.08x + 1.09$ $r = 0.97$	$y = 2.21x + 0.93$ $r = 0.98$	$y = 1.55x + 1.48$ $r = 0.96$	$y = 1.8x + 1.41$ $r = 0.98$
Mg	$y = 0.84x + 0.18$ $r = 0.95$	$y = 0.49x + 0.21$ $r = 0.98$	$y = 0.69x + 0.21$ $r = 0.98$	$y = 0.53x + 0.17$ $r = 0.96$	$y = 0.35x + 0.25$ $r = 0.97$	$y = 0.48x + 0.16$ $r = 0.97$
CEC	$y = 1.31x + 5.1$ $r = 0.83$	$y = -0.32x + 6.2$ $r = 0.43$	$y = 0.36x + 5.88$ $r = 0.69$	$y = 0.8133x + 5.49$ $r = 0.60$	$y = 0.5857x + 5.81$ $r = 0.93$	$y = 0.47x + 5.39$ $r = 0.89$
Potassium	$y = 10.67x + 27.27$ $r = 0.89$	$y = 2.013x + 57.5$ $r = 0.24$	$y = 10.43x + 65.43$ $r = 0.56$	$y = 20.61x + 39$ $r = 0.91$	$y = -26.69x + 121.21$ $r = 0.83$	$Y = -32.64x + 94.95$ $r = 0.88$

Soil pH increased as limestone rates were increased. Thus, pH was positively and closely related to limestone rates ($r = 0.98$) (Table 7). The combination of limestone + Tithonia and limestone + Tephrosia depressed the effect of limestone rates more than the other treatments probably because of release of organic acids from GM. The suggestion that organic matter input causes acidification in the short run, assumes that not all organic matter decomposes and therefore all the acid neutralising components in the organic matter are not released into the soil. Nitrification of ammonium ions released from green manures may also partly account for the lower pH observed with green manures incorporation.

4.4.2.2 Effects of limestone, MPR, GM and their combination on exchangeable aluminium

Exchangeable Al ranged from 0.4 - 2.8 cmol (+) kg⁻¹ (Appendix 1). All treatments with limestone above half of the lime requirement decreased exchangeable Al considerably and hence may have reduced the Al toxicity. Figure 8 shows the effect of limestone, MPR and GM on exchangeable Al in soil. Generally, there were negative correlations (Table 7) between exchangeable Al and limestone rates when limestone was applied alone, applied with green manures and/or with MPR. All the treatments had similar trends in decreasing exchangeable Al as the limestone rate increased.

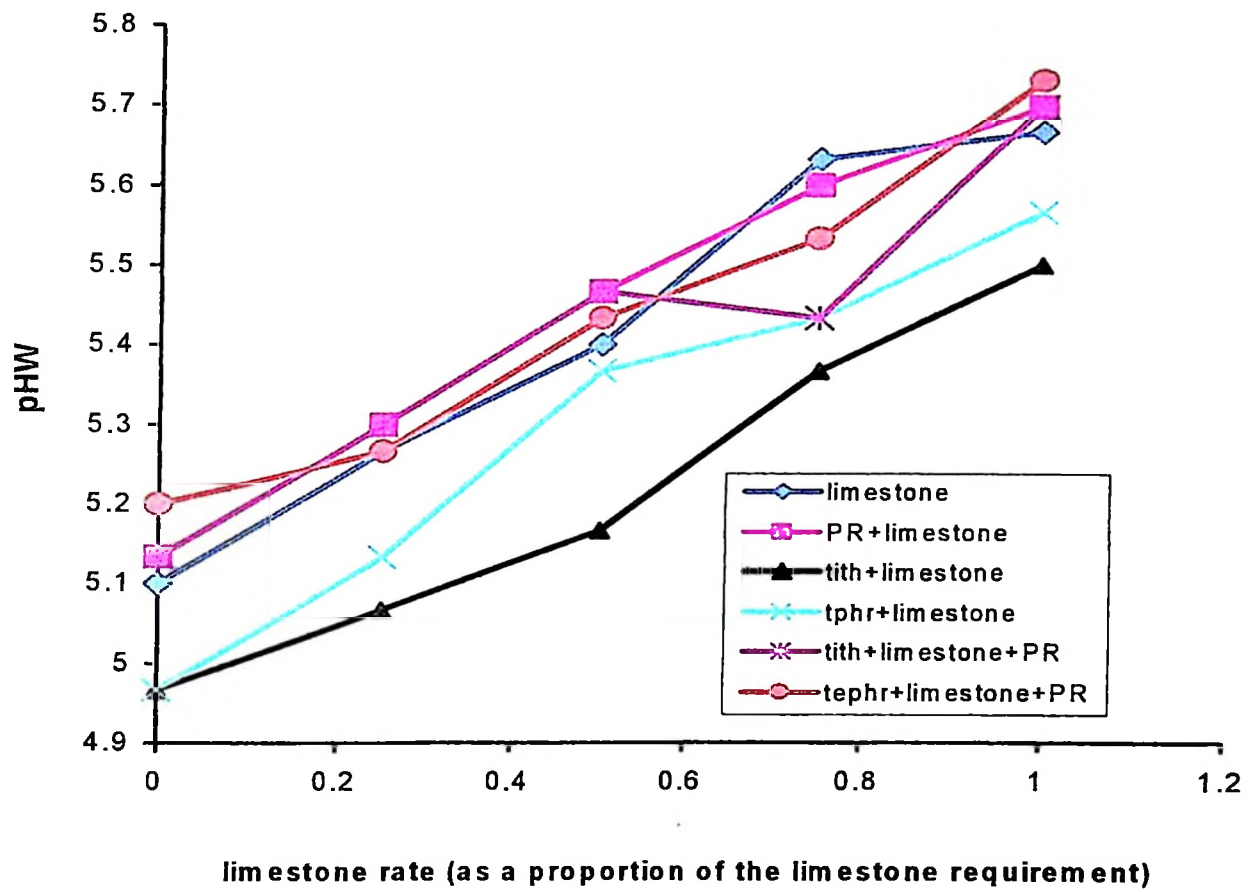


Figure 7. Effects of limestone, MPR, GM and their combination on pH (water) in the greenhouse experiment

There was a significant decrease in exchangeable Al in soils treated with PR + limestone, Tithonia + limestone + MPR, Tephrosia + limestone and Tephrosia + limestone + MPR over control (Appendix 1). Only limestone + MPR stands out at low rates of limestone below or equal to half of the lime requirement, because they complement each other for reducing exchangeable Al. At higher rate limestone had a dominant effect. Limestone was necessary to overcome the acidity. The beneficial effects of PR addition at low rates of limestone were probably due to its supply of Ca after dissolution. However the beneficial effect of PR at high rate of limestone was not observed probably because of reduction of PR dissolution arising from reduction of available protons.

It has been reported that CO_3^{2-} could reduce Al toxicity by the formation of AlCO_3^+ or AlOHCO_3 complexes, which are non-toxic to plants (Kamprath, 1970). However, even when limestone was applied at a rate equal to the lime requirement some exchangeable Al still remained in soil. May be the dissolution of limestone was not yet complete since this experiment lasted only for 42 days.

4.4.2.3 Effects of limestone, MPR and GM on exchangeable Ca and Mg

Liming increased exchangeable Ca and Mg from $1.06 - 3.4 \text{ cmol (+) kg}^{-1}$ and $0.20 - 1.13 \text{ cmol (+) kg}^{-1}$, respectively. With regard to the rating by Landon (1996), the Ca in the soil was ranked as low despite the limestone applied for some treatments. The treatments, which received limestone equivalent to half the neutralising level of

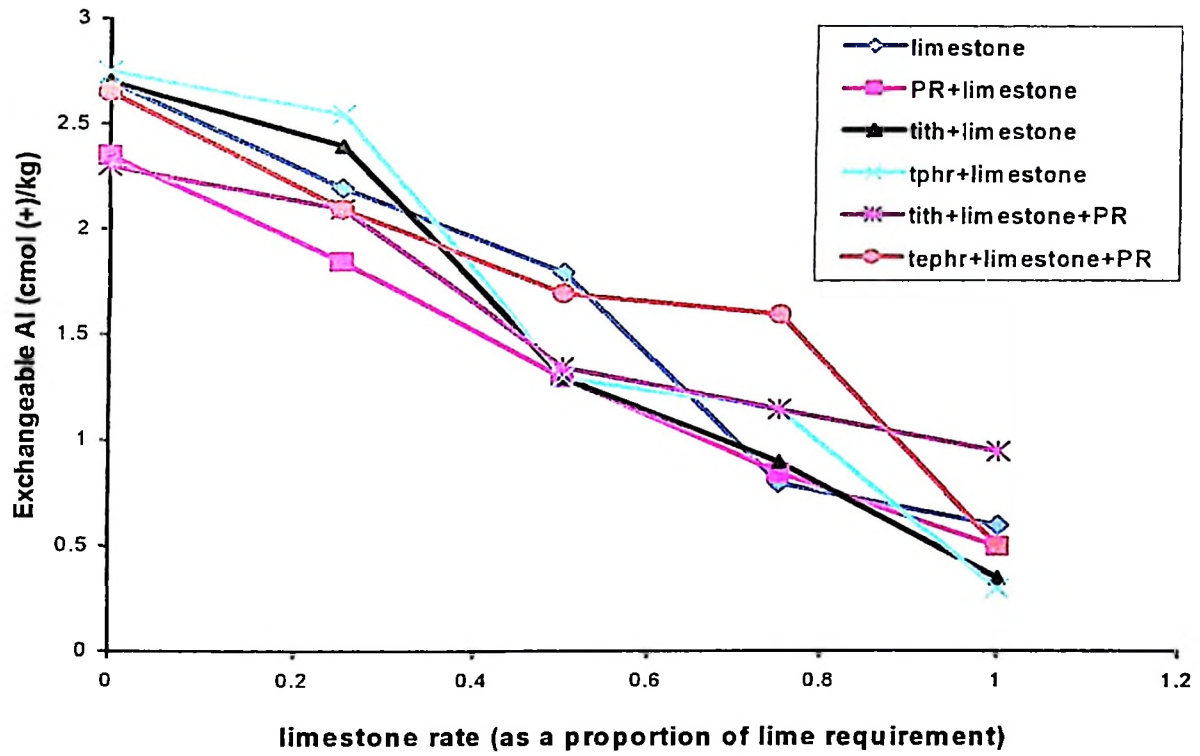


Figure 8. Effects of limestone, MPR, GM and their interaction on exchangeable Al in the greenhouse experiment

aluminium and above, increased exchangeable Mg in soils to high (> 0.5 cmol (+) kg^{-1}) according to the rating by Landon (1996).

Figures 9 and 10 show the effects of limestone, MPR and GM on exchangeable Ca and Mg, respectively. Generally, there were positive correlations (Table 7) between Ca and Mg and limestone rates when limestone was applied alone, applied with green manures and or with MPR. The major contributor of Ca is limestone and combination of limestone and MPR at limestone rates equal to or greater than half the lime requirement. The dominant factor on Mg was also limestone; other treatments had no effect or caused slight depression in Mg.

All the treatments gave similar trends for the Ca and Mg as limestone rates increased. There was a significant increase in exchangeable Ca in soils treated with PR + limestone, Tephrosia + limestone + MPR and Tithonia + limestone + MPR over the control soil. On the other hand, the effect of increasing limestone on increasing Ca was enhanced by MPR until the rate of 0.5 of the lime requirement. For example, the exchangeable Ca in MPR treatment was 163% of the check and the exchangeable Ca in 0.25 limestone + MPR treatment was 152% of 0.25 limestone treatment. These trends were not observed with Mg.

As it was discussed in the paragraph above, the addition of MPR at low rate of limestone had increased Ca due to supply of Ca after PR dissolution. Dolomitic lime supplied Mg to the soil and thus maintained a good balance between Ca and Mg in

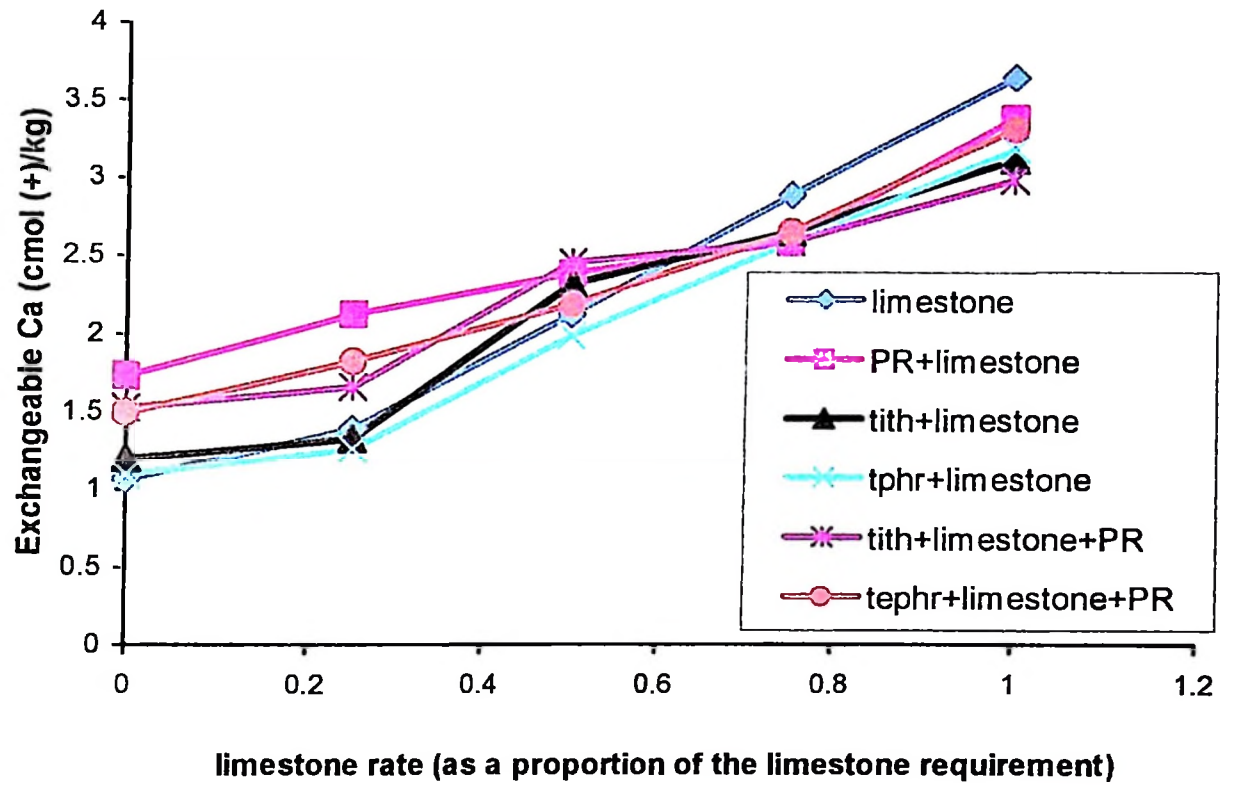


Figure 9. Effects of limestone, MPR, GM and their interaction on exchangeable Ca in soil samples from the greenhouse experiment

the soil and in the plant. Therefore, application of dolomitic lime is particularly important for crop production in acid soils amended with travertine, which has low Mg content.

Addition of Tephrosia GM decreased both Ca and Mg in the soil at the low rate of limestone. This could be due to the delay in the decomposition of Tephrosia than Tithonia. This phenomenon led to immobilisation of cations by microorganisms. In the presence of MPR, the same tendencies were not observed since some Ca and Mg were released after MPR dissolution.

4.4.2.4 Effects of limestone, MPR and GM on Bray 1 P

Extractable P in soil samples taken after completion of the greenhouse experiment ranged from 9.2 to 31.9 mg kg⁻¹. This range would be ranked as low to medium according to Landon (1996). The green manures in combination with MPR increased Bray 1 P levels, probably by decreasing fixation of P dissolved from MPR or by enhancing dissolution of MPR. Mutwewingabo (1987) reported that this soil has a high P adsorption capacity. This result suggests that high rates of P and the combination of P sources and manures will improve P availability in this soil.

Figure 11. shows the effect of limestone, MPR and GM on Bray 1 P. Generally, there were positive correlations (Table 7) between Bray 1 P and limestone rates when limestone was applied without MPR ($r = 0.9$, $r = 0.86$ and $r = 0.95$, respectively for

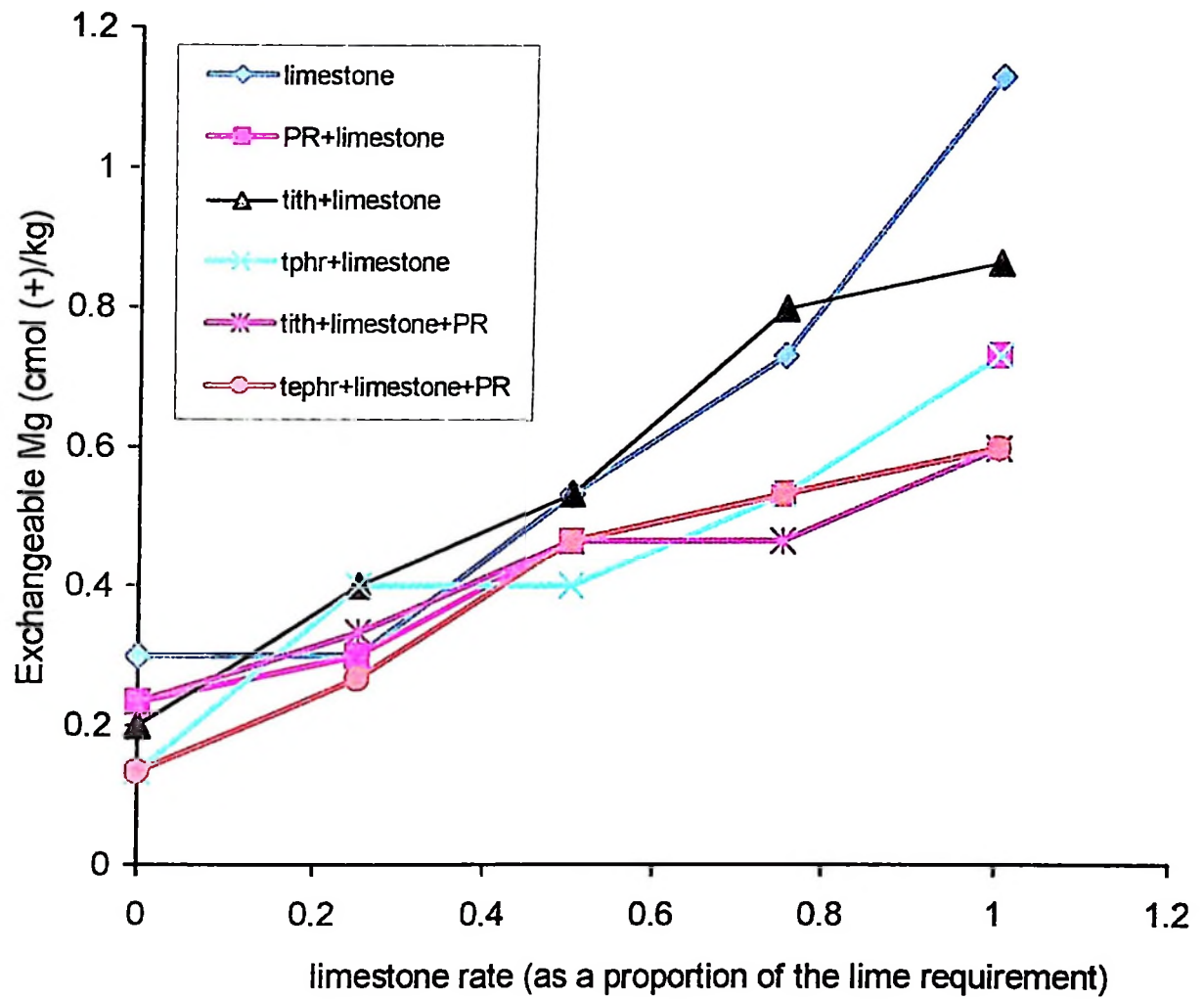


Figure 10. Effects of limestone, MPR, GM and their interaction on exchangeable Mg in soil samples from the greenhouse experiment

treatments with limestone alone, limestone + Tithonia and limestone + Tephrosia). Limestone applied along with MPR even with green manures addition gave negative correlations ($r = -0.97$, $r = -0.96$ and $r = -0.99$, respectively for MPR + limestone, Tithonia + limestone + MPR and Tephrosia + limestone + MPR treatments).

Limestone depressed Bray 1 P in the presence of MPR probably due to decreased dissolution of MPR. Addition of green manures (Tithonia and Tephrosia) improved Bray 1 P in all treatments but did not change the trend of the curves. The effect of Tithonia was more effective in increasing Bray 1 P than Tephrosia. The effect of MPR was high on Bray 1 P even where limestone was applied at a rate sufficient to neutralise exchangeable Al.

The high quantities of P in the treatments with MPR were due to P input from MPR. In acid soils, even when lime is applied in soil with very low P status it is not possible to increase available P appreciably. Green manures plus MPR resulted in higher increase in Bray 1 P (Figure 11). This could be due to the enhancement of MPR dissolution or/and the addition of P from the green manures.

The effect of green manures in enhancing MPR dissolution can be explained by the decomposition of the green manures, which could have modified soil conditions through the release of organics acids (Tian *et al.*, 1992; Zaharah and Bah, 1997). Evidence currently available suggest that these acids can enhance dissolution of elements from minerals due to their acidity and to a greater extent by complex

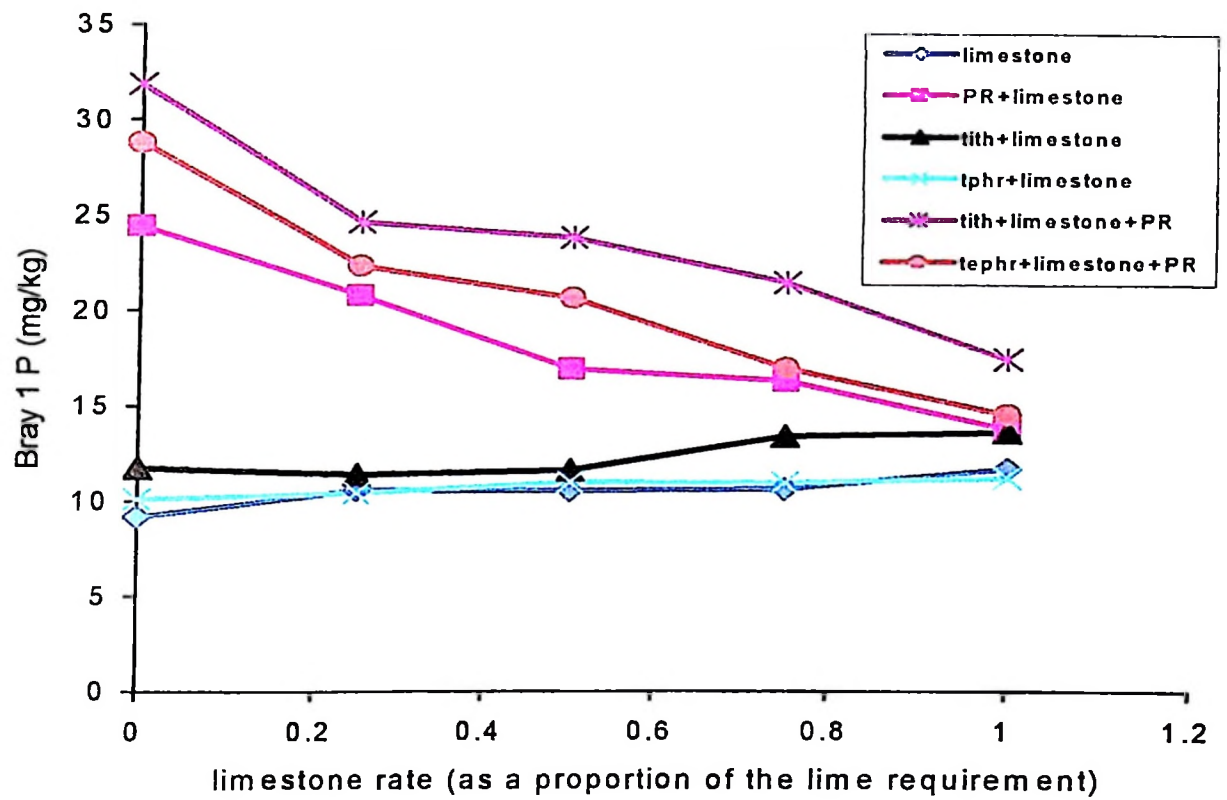


Figure 11. Effects of limestone, MPR, GM and their interaction on Bray 1 P in the greenhouse experiment

formation (Zaharah and Bah, 1997). Consequently, the increased solubility of the MPR probably involved the chelation of Ca from the MPR resulting in increased P release (Chien, 1992).

Furthermore the organic acids could increase the availability of P by reducing adsorption and fixation (Yang *et al.*, 1994). For example, Nziguheba *et al.* (1998) found that applications of 5 t ha⁻¹ of Tithonia increased the sum of resin + NaOH extractable P when compared to additions of similar amount of P as TSP. The increase in available P might be related to a decrease in the P-adsorption capacity of the soil with addition of green manures. Ohno and Crannell (1996) observed that soluble organic matter from green manure was of lighter molecular weight and had a greater effect in reducing P adsorption than the soluble organic matter fraction with higher molecular weight. In addition, the influence of organic materials on P availability is also related to the quality of the organic materials. Iyamuremye *et al.* (1996a) found that addition of high quality alfalfa and low quality wheat straws with comparable carbon concentration but different P concentration had different effects on P adsorption. Addition of two high quality organic residues (alfalfa and manures) with comparable P concentration but different C concentration, on the other hand, had comparable reduction in P adsorption. They attributed the effect to saturation of P sites by organic anions. The reduction in P adsorption with Tithonia in this study indicates that the former mechanism, i.e. organic anions competing with phosphate anions is the most likely explanation.

4.4.2.5 Effects of limestone, MPR and GM on soil CEC, OC and exchangeable K

Exchangeable K ranged from 0.05 – 0.19 cmol (+) kg⁻¹. This range would be ranked as low according to Landon (1996). Green manures improved the exchangeable K level but the values were still in the low range according to Landon (1996). The results showed that the CEC ranged from 5.2 – 6.4 cmol (+) kg⁻¹ and therefore, according to the rating by Landon (1996), the CEC values in the soil after harvesting maize, were low.

The correlations between CEC and limestone rates were positive and high for the treatments with limestone alone ($r = 0.83$), Tithonia + limestone + MPR ($r = 0.93$) and for Tephrosia + limestone + MPR ($r = 0.90$). The rest of the treatments had weak correlations with the CEC. Increased CEC with limestone rates was not sharp, the same trend is observed for nitrogen and K. The soil on which the experiment was carried out could be having variable charge so the limestone could have increased the electro negativity thus increased also CEC.

Green manures increased organic matter with the effect of Tephrosia being higher than that of Tithonia (The results are presented in Appendix 1). Tithonia decomposition is faster than Tephrosia, which could lead to less organic carbon from Tithonia than from Tephrosia and less residual effects than Tephrosia. The nitrogen content of plant material is an important factor controlling the rate of decomposition and N mineralisation. A high N content of plant materials favours N mineralisation, leading to a high rate of decomposition.

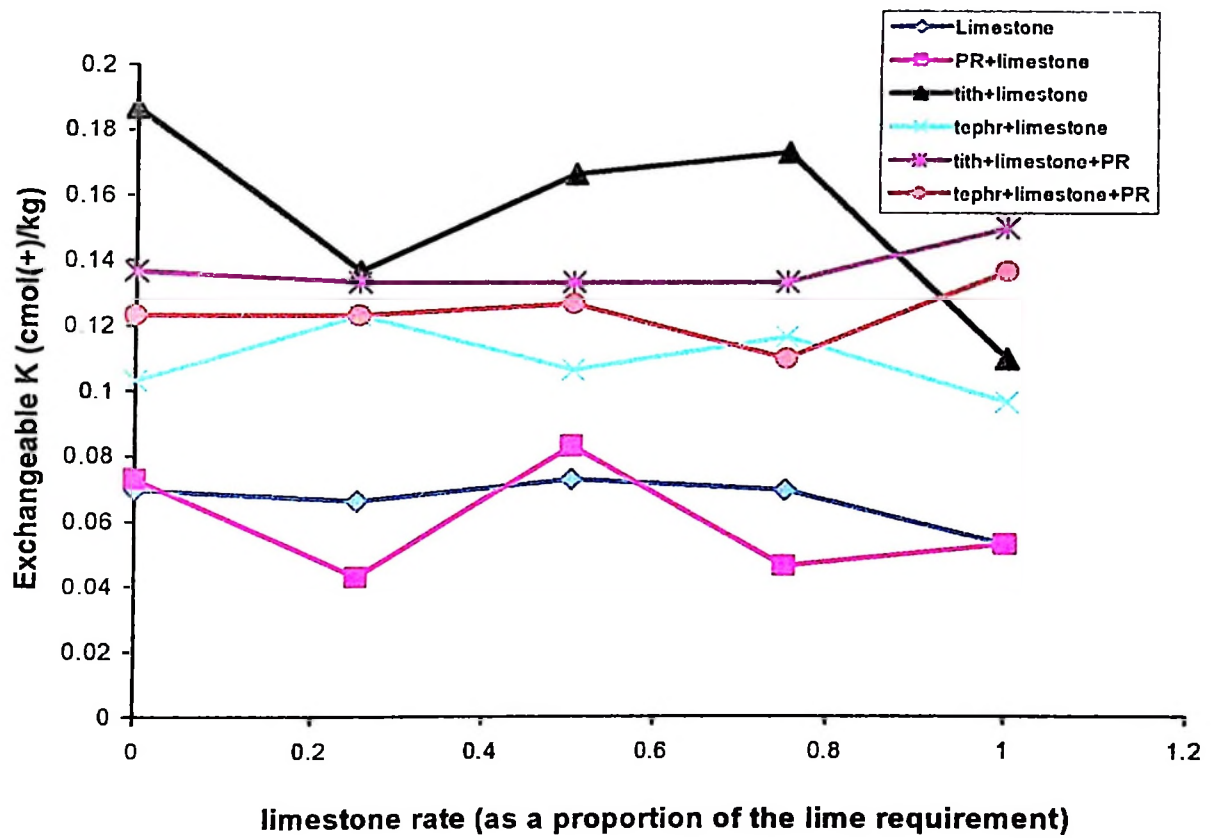


Figure 12. Effects of limestone, MPR, GM and their interaction on exchangeable K in soil from the greenhouse experiment

The relationship between K and limestone rate were positive but weak (Table 7). Addition of MPR and/or green manures enhanced exchangeable K in the soil. The effects of green manures were pronounced for increasing exchangeable K in the soil with Tithonia being higher than Tephrosia. The main contributor to increase in exchangeable K was organic material. As it was discussed for N, the slow decomposition of Tephrosia could account for this observation. The lime rate equal to the lime requirement had a negative effect on exchangeable K in the soil. This might be caused by an imbalance between bases e.g. Ca/K. When this ratio is high, K is likely to be leached.

4.5 Field experiment

4.5.1 Effect of limestone, MPR and GM on yield and soil properties

The effects of lime, MPR and GM (Tithonia and Tephrosia) on yield are presented in Table 8 while selected soil properties of soil samples taken from experimental plots are presented in Table 9. Overall, all treatments had very high significant influence on all parameters (yield, pH, Al, H, total acidity, Ca, Mg, Brayl P, CEC, total P and total N) ($P < 0.001$) except for organic carbon ($P = 0.961$)

4.5.1.1 Effect of limestone, MPR and GM on maize yield

Limestone alone increased the yield by 13.5 times compared to check treatment while the NPL treatment increased yield by 8.9 times. The MPR alone significantly increased maize yield compared to the check, NPL, Tephrosia and limestone alone

by 2107%, 122.5%, 125% and 63.7%, respectively. The yield of recommended fertilizer combination (NPKL) was higher than NPL, MPR alone, limestone alone, Tithonia alone, Tephrosia alone, Tephrosia + MPR and Tithonia + limestone by 277.2%, 29.8%, 112.4%, 26.6%, 192.05, 6% and 12.7%, respectively. The yield of Tithonia treatment was 22.7 times that of the check treatment and 231% of the Tephrosia treatment while for the Tithonia plus MPR, yield was 114% of Tephrosia + MPR. Tephrosia alone increased yield by 9.8 times compared to the check treatment but the yield was still low compared to other treatments. The combination of limestone and Tithonia had higher yield than limestone alone and Tithonia alone. The yield of Tithonia + limestone treatment was 188.5% of that of limestone alone and 112% of

Table 8. Effect of limestone, MPR and GM on maize yield

Treatments	Yield (kg ha ⁻¹)
Control	148j
MPR	3 267g
Limestone	1 996h
Tithonia	3 349g
Tephrosia	1 452i
Tephrosia + MPR	3 993e
Tithonia + MPR	4 554c
Tithonia+Limestone	3 762f
Tephrosia+Limestone	4 323d
NPL	1 468i
Tithonia+Limestone+PR	5 594b
Tephrosia+Limestone+PR	5 907a
NPKL	4 240d
CV %	11.1

Means in the same column followed by the same letter(s) are not significantly different according to Duncan Multiple Range Test at 0.05 levels.

that of Tithonia alone. On the other hand Tephrosia + limestone had higher yield than either limestone alone or Tephrosia alone. Tephrosia + limestone yielded 216% of limestone alone and 297.7% of Tephrosia alone. The combination of three amendment improved yield even further with Tephrosia + limestone + MPR having the highest (5907 kg ha⁻¹) followed by Tithonia + limestone + MPR (5594 kg ha⁻¹).

The high yield associated with MPR alone may be due to improvement in P supply in this soil, which had very low P status. Also MPR supplied Ca and reduced soil acidity slightly while limestone could have reduced Al toxicity and supplied Ca and Mg and hence favoured good growth.

The high yield associated with Tithonia GM may be due to higher contents of P, N and K and faster release of the nutrients from Tithonia than from Tephrosia. The short-term immobilisation of P and slower provision of N and K resulting from application of the lower quality Tephrosia, could have negatively affected the early growth of maize in the treatment with Tephrosia alone. The high yield of the combination of three amendments was more likely due to a higher supply of N, P and K and better root growth due to elimination/decrease of Al toxicity.

The small response to N and P from inorganic fertilizers cannot easily be explained given that N and P were applied at the same rate for organic inputs. One possibility is that since K is limiting in this soil (Table 9) the application of lime and high rate of N might have aggravated the K problem. This explanation is supported to some

degree by the high response to inorganic N and P when the K was not a limiting factor (Jama *et al.*, 2000) as well as the NPKL treatment in this study. These yields with organic inputs illustrate the difficulty in interpreting such data because organic matter adds several nutrients and the amount; ratio and release of nutrients added from the different organic materials vary (Palm *et al.*, 1997). It is therefore difficult to relate differences in yield to one nutrient alone unless all other nutrients are added in adequate quantities. The fact that crop growth in this study was limited by many nutrients (N, P, K, Ca and Mg and micronutrients) also makes it difficult to compare yields and nutrient uptake from the organic treatments that supply many nutrients at the same time compared to NPL treatment. Organic matter amendments improve soil physical proprieties, which can account to improve yield comparatively to inorganic fertilizers.

The high yields from the treatments with three amendments could be explained by the alleviation of many constraints at the same time such as decrease of Al toxicity and increase in P, K, N, Ca and Mg supply. The high yield of maize is due to improvement of many factors, which were limiting growth and yield. In addition the application of limestone might have improved root growth and distribution in soil. The greater root growth may have led to increased uptake of P and others nutrients.

4.5.1.2 Effect of limestone, MPR and GM on field soil properties

The results for residual soil nutrients are given in Table 9 and indicate that after harvesting, the properties of the soil were improved in all treatments compared to the

check but in general their levels were still low. The exchangeable calcium was very low-to-low even for the treatments where limestone was applied (0.67 - 2.1). The same trend was observed for Mg (0.23 - 1.3). All treatments, which received limestone, were moderately acid.

In all treatments the CEC are less than 10 cmol (+) kg⁻¹, which is rated as low. The Bray1 P in the soil even treated with either MPR or TSP was low; indeed in the check the phosphorus is very low (<3 mg kg⁻¹).

Plots treated with either MPR alone or combinations of GMs and MPR gave higher Bray1 P than those treated with MPR mixed with GMs and limestone. Addition to the soil of MPR and MPR-GMs mixtures on average increased Bray 1 P from 3.0 to 14.3 mg kg⁻¹ and total P from 214.0 to 331.5 mg kg⁻¹ representing increases of 376.7% and 54.9%, respectively. MPR-green manure application also increased Bray 1 P and total P by 116.7% (from 6.6 to 14.3) and 6.7% (from 310.7 to 331.5%) as compared with MPR-green manure-lime treatments, respectively.

This was probably due to the effect of CaCO₃ on the dissolution of MPR. Low pH, low exchangeable Ca and low P are the major soil factors known to increase dissolution and subsequent P release from PRs (Khasawneh and Doll, 1978; Chien *et al.*, 1980; Smyth and Sanchez, 1982; Bolland and Gilkes, 1990). Addition of CaCO₃ increased soil pH and exchangeable Ca. This may account for the low available P, presumably through a decrease in the availability of protons and a decrease in the size of the calcium sink in the soil (Hanafi *et al.*, 1992; Robinson *et al.*, 1992). MPR

addition slightly increased soil pH, which probably resulted from the consumption of protons during the PR dissolution or through neutralisation of soil acidity by accessory carbonates in the PR. The application of both travertine and dolomite increased exchangeable Ca and Mg.

The exchangeable Ca and Mg is another factor responsible for the decrease in the dissolution of the PR material. This observation is in agreement with the findings of He *et al.* (1996) on dissolution of North Carolina PR. Dissolution of the PR is increased by the removal of Ca and H_2PO_4^- from the soil solution, provided the pH is sufficiently low (Robison and Syers, 1990)

Application of limestone alone increased Bray 1 P by 100% relative to the control. These results are similar to those of Martini *et al.* (1974) who observed a reduction in fixation of added P fertilizer with liming. Roberston *et al.* (1974) found that liming soils high in sesquioxides increased P availability, whereas liming soils low in sesquioxides had no effect on P availability. The experimental soil was highly weathered, therefore, might have high sesquioxides. On the other hand, other studies have failed to show increases in available P with liming (Pearson, 1975; Reeve and Summer, 1970).

Table 9. Selected chemical properties of soils from experimental plots after maize harvest as influenced by limestone, MPR and GM

	pHw	KClpH	Al	II	total acidity	Ca	Mg	K	CEC	Brayl P	Total P	OC
						cmol (+) kg ⁻¹				—(mg kg ⁻¹)—		(%)
Control	4.9h	3.87e	3.0a	0.90a	3.9a	0.67f	0.23d	0.07i	5.8f	3.0h	214.0e	1.86
MPR	5.2fg	4.07d	2.2d	0.47b	2.7d	1.2cde	0.47cd	0.07i	6.1ef	17.7a	328.7b	1.67
Limestone	5.6abc	4.20bc	1.4fg	0.40bc	1.8fg	1.7b	1.0ab	0.08h	6.5cdef	6.0gf	283.7c	1.81
Tithonia	5.1g	3.93e	2.4cd	0.50b	3.3bc	0.8ef	0.43cd	0.13c	6.3def	8.5e	253.3cd	1.67
Tephrosia	5.1g	3.93e	2.9ab	0.73a	3.6ab	0.9def	0.57cd	0.13c	7.3cb	5.7fg	266.7cd	2.05
Tephrosia + MPR	5.3ef	4.13dc	2.6bcd	0.30bc	2.9d	1.3c	0.60c	0.13b	8.9a	14.4b	330.7b	1.78
Tith. + MPR	5.3ef	4.10d	2.7abc	0.27bc	3.0cd	1.2cd	0.43cd	0.15a	6.7bcdef	10.7c	335.0b	1.78
Tithonia+Limestone	5.7ab	4.37ab	1.4fg	0.33bc	1.8fg	1.7b	0.93b	0.10f	6.9bcde	5.1g	254.7cd	1.693
Teph+Limestone	5.6bc	4.43a	1.4fg	0.27bc	1.7fg	2.1a	1.00ab	0.10g	7.6b	5.0g	272.0cd	1.787
NPKL	5.4ed	4.27b	1.9e	0.43b	2.3e	2.0ab	1.00ab	0.03j	6.3cdef	10.4cd	282.3cd	1.86
Tith+Limestone+PR	5.7ab	4.37ab	1.4fg	0.37bc	1.8fg	1.9ab	1.20ab	0.13b	7.1bcd	7.2ef	378.3a	1.8
Teph+Limestone+PR	5.8a	4.37ab	1.3g	0.17c	1.5g	2.1a	1.33a	0.12d	7.5b	8.9de	337.7b	1.823
NPKL	5.5cd	4.27b	1.7ef	0.37bc	2.0ef	1.8ab	0.33cd	0.11e	6.2def	7.1ef	267.3cd	1.83
CV %	1.6	1.7	9.3	30.2	9.3	13.2	25.1	6.2	7.6	11.9	5.4	15.7

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.

The effects of limestone, MPR, GM and their combination on exchangeable K are given in Table 9. Plots where mineral K or organic fertilisers were not applied (plots treated with NPL, MPR and limestone) gave lower K levels than others. Application of lime significantly decreased exchangeable K in the soil. The above observation concur with that of Curtin and Smillie (1995) that liming decreases exchangeable K. Mixing NPK with burned lime resulted in lower Mg as compared with that from other plots treated with limestone alone or a combination of limestone with MPR and/or green manure.

Liming has been shown to increase K retention, leading to K deficiency on freshly limed soils (Mtenga, 2000). This effect is thought to result from the opening up of selective exchange sites on soil colloids which were blocked by Al at low pH or from lowered percent K saturation caused by increased CEC. These reactions lead to a decrease in soil solution K and K uptake by plants, which may cause K deficiency (Magdoff and Bartlett, 1980).

Liming increased pH in water from 4.9 to a range of 5.6 to 5.8. Green manure, and MPR and their combination also increased pH slightly. MPR decreases soil acidity and increases pH because its dissolution consumes protons and substitutes the protons with Ca and Mg. Khasawneh and Doll, (1978) and Sanyal and Datta, (1991) have reported similar effects with other PRs.

Application of limestone alone or in combination with MPR and green manures, on average decreased total soil acidity by 55.9% (from 3.9 to 1.72) and increased exchangeable Ca from 0.67 to 1.9 cmol (+) kg⁻¹ and Mg from 0.23 to 1.1 cmol (+) kg⁻¹. The Ca/Mg ratios were within 1 to 10 for all treatments. This range is considered optimum for crop growth. Plots treated with MPR or MPR + green manures on average decreased exchangeable Al by 20% (from 3.0 to 2.5) relative to the control treatment. No significant effect of green manures alone on soil acidity properties relative to other amendments used was observed, but *Tithonia* green manure decreased exchangeable Al by 25% relative to the control treatment. However, there was no significant difference between exchangeable Al in the *Tephrosia* treatment and the control.

Liming decreased exchangeable Al considerably to a level considered safe for most crops. The Al saturation decreased from 52% to 20%. Only very sensitive crops may be affected by this Al saturation level (20%) according to Landon (1995). Liming also increased exchangeable Ca and Mg.

The relative increase in pH and decrease of Al toxicity on addition of green manures relative to the control may be attributed to self-liming effect due to the high concentration of cations in the green manures, which were released on mineralisation (Hue, 1992; Hoyt and Turner, 1975). Malcolm *et al.* (1998) cited by Savini (1999) working with three fallow types found that *Tithonia* fallows were associated with high soil cation (K, Ca and Mg) status and relatively higher pH than the other fallows. Since addition of green manures increases soil pH, the PR dissolution was

reduced where green manures were applied in combination with PR. However, this increase in pH with green manures is important for P uptake (Table 10). Increasing pH will cause precipitation of exchangeable Al and Fe, thus reducing the potential for PO_4 precipitation. In acid soils, exchangeable acidity can react readily with PO_4 , reducing the availability of PO_4 for plant uptake. Thus, reduction of exchangeable acidity by soil amendments may be an important mechanism for reducing P sorption.

The reduction of exchangeable acidity by green manures in the soil may be explained partly by the concomitant increases in pH where green manures were applied (Table 9). This reduction may be caused by: precipitation of Al ions by OH ions released from exchange of ligands between organic anions and terminal hydroxyls of Fe and Al oxides, and/or complexation of Al by organic molecules (Hue, 1992). This agrees with the findings of Kamprath and Cyde (1970) that less Al in the soil solution accompanied the increase in organic matter content of soil at any given pH. This decrease in exchangeable acidity on addition of green manures reduces the number of sites available to adsorb P released from PR, which is another possible explanation for the increased P uptake in the treatments, which received MPR in combination with green manures (Table 10).

4.5.2 Nutrient concentration in maize leaves

As illustrated in Table 10 application of limestone, MPR and GM (Tithonia and Tephrosia) significantly ($P < 0.05$) increased N, P, K, Ca, Mg and Cu concentrations in maize leaves except Zn ($P = 0.907$).

The data indicate that the most serious nutrient deficiencies in the absolute control treatment were P and K. This assessment is based on a P concentration value of 0.08% which is much lower than the sufficiency range of 0.25 – 0.40% reported by Tandon (1995) and K concentration value of 0.24% which is also much lower than the sufficiency range of 1.7 – 2.5% in maize plants reported by Jones and Eck (1973). The next limiting nutrient was nitrogen with a value of 2.2% in control plants, which would be rated as low according to Tandon (1995). Tandon (1995) rated N concentration values of < 3.5% as low and those between 3.5 – 5% as sufficient while those > 5% are rated as high for maize growth. The concentration of Ca, Mg, Cu and Zn in the control plants all fell in the sufficiency ranges according to Tandon (1995). Similar observations were found in results of the pot experiment.

All the treatments increased P concentration in leaves significantly. The biggest increase occurred in the NPL treatment, which gave a concentration of 0.22%, which was close to the sufficiency level. Combination of green manures and MPR and GMs + Limestone + MPR treatments caused an intermediate increase in P with values ranging from 0.14% - 0.16%. The high uptake of P from the combination of MPR and GM with or without limestone treatments might be due to the effect of the organic additions on P availability in soils.

The mixing of PR with limestone is thought to depress PR dissolution and plant P uptake and hence decrease yield. However, although Ca influences the dissolution of PR in the absence of plants, in the presence of plants the continuous uptake of Ca

during the plant growth may have masked this effect. Saggar *et al.* (1993) observed the same effect when working with PRs in high P sorption soils

All the treatments increased K concentration in leaves significantly except the NPL treatment, which decreased K concentration in leaves significantly. The biggest increase occurred in the combination of GMs and MPR treatment, which gave K concentration values ranging from 0.88 – 0.99%. However this range is still very low relative to the critical range published by Landon (1995). Green manures alone, NPKL and combination of GMs, limestone and MPR treatments resulted in intermediate increases in K with values ranging from 0.70% - 0.80%.

Table 10. Effects of limestone, MPR and GM on nutrient concentrations in maize leaves from the field experiment

Treatments	N	P	K	Ca	Mg	Cu	Zn
	— (%) —			— (mg kg ⁻¹) —			
Control	2.20g	0.08g	0.24e	0.44e	0.26d	25.8	36.5abc
MPR	2.63f	0.12d	0.42d	0.50e	0.33bcd	22.1	17.6bcd
Limestone	2.53f	0.11e	0.45d	0.62d	0.42b	5.0	15.1cd
Tithonia	3.27dc	0.11e	0.72c	0.46e	0.29cd	20.1	39.0ab
Tephrosia	2.83e	0.10f	0.80cb	0.44e	0.27d	16.2	29.0abcd
Tephrosia + MPR	3.33c	0.14c	0.88ab	0.64cd	0.40bc	17.8	13.8d
Tithonia + MPR	3.40bc	0.14c	0.99a	0.62d	0.44b	18.1	36.5abc
Tith. + Limestone	3.40bc	0.12d	0.66c	0.70bc	0.31cd	15.7	27.7abcd
Teph. + Limestone	3.13d	0.10f	0.70c	0.65bcd	0.39bc	19.1	29.5abcd
NPL	3.40bc	0.22a	0.16e	0.84a	0.55a	19.9	8.8d
Tith. + Lim. + MPR	3.60a	0.16b	0.68c	0.72b	0.26d	14.9	45.1a
Teph. + Lim. + MPR	3.50ab	0.14c	0.79cb	0.72b	0.39bc	17.4	36.7abc
NPKL	2.83e	0.12d	0.78cb	0.64cd	0.31bcd	12.0	45.3a
CV %	3.36	10.4	12.9	5.8	16.4	46.7	39.5

Means in the same column followed by the same letter(s) are not significantly different according to Duncan Multiple Range Test at 0.05 levels.

The higher uptake of K from the combination of MPR and GM with or without limestone than from other treatments might be due to the effect of the organic additions on K availability in soils.

The negative influence of limestone on K uptake in the NPL treatment could be due to increased imbalance of K with Ca and/or Mg, which are higher in limed plots or a depression of K uptake by NH_4^+ . This treatment had also received high rate of inorganic N which might have enhanced the imbalance between NH_4^+ and K.

Nitrogen concentration in leaves was increased significantly by all amendments used in the trial. The biggest increase occurred in the NPL, Tithonia + MPR, Tithonia + limestone and the combination of GMs, MPR and limestone treatments, which gave concentration values ranging from 3.4 – 3.6%, which was in the sufficiency level. Tephrosia, NPKL, Tephrosia + limestone Tephrosia + MPR treatments caused intermediate increases in N with values ranging from 2.83 – 3.33% which was close to the sufficiency level. Tithonia green manures supplied more N to maize plants than Tephrosia green manure. This observation supports the idea that the quality of organic inputs affects nutrient availability patterns and crop growth.

All the treatments increased Ca and Mg concentration in leaves significantly. The biggest Ca increase occurred in the NPL, combination of GMs and MPR and limestone, Tephrosia + limestone and Tithonia and limestone treatments, which gave concentration values ranging from 0.65 – 0.84%. Limestone alone, Tithonia + MPR, Tithonia + MPR and NPKL treatments caused intermediate increases in Ca with

values ranging from 0.62 – 0.64%. While for Mg, the biggest increase occurred in the NPL, Tithonia + MPR, Tithonia, Tephrosia + limestone and the combination of Tephrosia, MPR and limestone treatments which gave concentration values ranging from 0.39 – 0.55%. The fact that Ca and Mg in the control plants fell in the sufficiency range indicates that the role of liming was mainly in decreasing Al toxicity rather than in correcting Ca and Mg deficiencies.

Although the exchangeable Ca and Mg were low in the soil in the control plot (Table 9), the concentrations of these nutrients fell in the critical range. This observation could be due to the low CEC and may also be due to the type of clay in the soil used. When CEC is low and the clay type is 1:1 (e.g. kaolinitic), available Ca and Mg in soil solution tend to be high compared to soils with high CEC and containing 2:1 clays e.g. montmorillonite.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

This study demonstrated that:

- (i) There are many constraints to crops production in acid soils in Tonga. Some of the most serious problems are Al toxicity and P, K and N deficiencies, which were alleviated appreciably by a combination of amendments.
- (ii) Limestone application was found to reduce exchangeable Al, increase Ca and Mg status in soils and uptake of these nutrients. In the greenhouse study however, high rates of limestone above quarter of the lime requirement were found to decrease yield and nutrient uptake.
- (iii) The addition of GMs to soil significantly increased exchangeable K in soil and plant uptake of N and K. Combination of GMs and MPR was found to increase Bray 1 P and P uptake in greenhouse.
- (iv) The extent of the influence of GM was observed to be dependent on the their quality. Tithonia GM was found to have high quality and provided N and K in quantities and rates relatively sufficient to increase crop yield substantially compared to Tephrosia.

(v) The suitable combination of amendments in the greenhouse study was the mixture of MPR, Tithonia and limestone at a rate equal to a quarter of lime requirement. For the field experiment high yield was obtained from the mixture of limestone, MPR and GMs.

(vi) The results from the greenhouse study revealed that high rates of limestone application have a negative effect on MPR dissolution as well as the uptake of K and P.

(vii) The amendements provided substantial residual effects in both field and pot experiments. Limestone increased soil pH, exchangeable Ca and Mg, and decreased exchangeable Al. MPR increased extractable P while GMs contributed in increasing exchangeable K.

(viii) Despite the increase in P and K concentrations in the pot and field experiments caused by the amendments, the concentrations were still below the critical range indicating that higher rates of the amendments were required.

(ix) High rates of limestone depress MPR dissolution.

From the findings of this study, the following recommendations were made:

- (i) farmers in Rwanda should be advised to apply Tithonia to supply both N, K and a small amount of P and find niches for tithonia biomass production,
- (ii) Since limestone is not yet used by farmers, there is need to create awareness for using limestone rather than burned lime to farmers and decision makers,
- (iii) Since MPR is not produced in Rwanda, economic analysis of its use must be undertaken,
- (iv) This study should be continued in various soils of different P fixation capacity and investigate long term effects in order to gain more knowledge on the interaction of MPR, limestone and green manures and on crop growth and nutrient uptake.

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APPENDICES

Appendix 1. Effects of limestone, MPR, GM and their interaction on selected soil properties from the greenhouse experiment

Table a. Effects of limestone on selected soil properties

	pHw	pHKCl	Al	H	Ca	Mg cmol (+) kg ⁻¹	K	CEC	Bray 1 P mg kg ⁻¹	OC %
LO	5.1c	4.1c	2.83a	1.73a	1.06d	0.30b	0.07a	5.23c	9.2b	1.46
L1	5.3bc	4.2b	2.03b	1.13b	1.40dc	0.30b	0.07a	5.63cb	10.6a	1.50
L2	5.4b	4.3b	1.73b	0.96bc	2.13bc	0.53b	0.07a	5.33c	10.5a	1.46
L3	5.6a	4.5a	0.76c	0.70c	2.90ab	0.73ab	0.07a	5.76b	10.6a	1.50
L4	5.7a	4.6a	0.60c	0.28d	3.66a	1.13a	0.05b	6.80a	11.7a	1.46
CV %	2.1	3.4	15.5	20.6	22.4	38.9	33.9	3.8	5.6	3.0

Any two means not followed by the same letter down a column are significantly different at P = 0.05

Table b. Effects of combining Tithonia green manure and different rates of limestone on selected soil properties

	pHw	pHKCl	Al	H	Ca	Mg Cmol (+) kg ⁻¹	K	CEC	Bray 1 P mg kg ⁻¹	OC %
LO	5.1ab	4.1b	2.83a	1.73a	1.06c	0.30c	0.07c	5.23c	9.2c	1.46
LO tithonia	5.0b	4.1b	2.70ab	0.43b	1.20c	0.20c	0.19a	5.70b	11.7b	1.50
L1 tithonia	5.1ab	4.1b	2.26b	0.43b	1.33c	0.40bc	0.14a	6.13a	11.4b	1.50
L2 tithonia	5.2ab	4.5a	1.30c	0.30b	2.33b	0.53b	0.17a	6.20a	11.6b	1.56
L3 tithonia	5.4a	4.6a	1.06c	0.26b	2.66ab	0.80a	0.17ab	6.10a	13.4a	1.56
L4 tithonia	5.5a	4.7a	0.50d	0.41b	3.13a	0.86a	0.11c	6.16a	13.6a	1.60
CV %	4.3	4.1	15.9	30.9	20.2	22.1	18.6	2.5	7.0	2.7

Any two means not followed by the same letter down a column are significantly different at P = 0.05

Table c. Effects of combining Tephrosia green manure and different rates of limestone on selected soil properties

	pHw	pHKCl	Al	H	Ca	Mg cmol (+) kg ⁻¹	K	CEC	Bray 1 P mg kg ⁻¹	OC %
LO	5.1cb	4.1d	2.83a	1.73a	1.06d	0.30cd	0.07b	5.23d	9.2b	1.46
LO Tephrosia	5.0c	4.2cd	2.66a	0.66b	1.10d	0.13d	0.10a	5.33cd	10.1ab	1.80
L1 Tephrosia	5.1cb	4.3c	2.46a	0.50bc	1.26d	0.40cb	0.12a	6.00ab	10.4a	1.66
L2 Tephrosia	5.4a	4.4b	1.30b	0.56bc	2.00c	0.40cb	0.11a	5.80cb	11.0a	1.63
L3 Tephrosia	5.4a	4.5b	1.16b	0.46bc	2.60b	0.53b	0.12a	5.96ab	11.0a	1.63
L4 Tephrosia	5.6a	4.8a	0.40c	0.13c	3.20a	0.73a	0.10a	6.36a	11.2a	1.63
CV %	2.8	2.9	20.7	33.0	17.0	25.9	13.8	4.8	5.7	3.8

Any two means not followed by the same letter down a column are significantly different at P = 0.05

Table d. Effects of combining MPR and different rates of limestone on selected soil properties

	pHw	pHKCl	Al	H	Ca	Mg cmol (+) kg ⁻¹	K	CEC	Bray 1 P mg kg ⁻¹	OC %
LO	5.1d	4.1d	2.83a	1.73a	1.06e	0.30c	0.07abc	5.23b	9.2d	1.46
LO MPR	5.1d	4.2d	2.40a	0.60b	1.73d	0.23c	0.07abc	6.40a	24.5a	1.46
L1 MPR	5.3cd	4.3c	1.93b	0.56b	2.13c	0.30c	0.04c	6.10a	20.8b	1.50
L2 MPR	5.5bc	4.4c	1.33c	0.44cb	2.40bc	0.46b	0.08a	5.80ab	17.0c	1.43
L3 MPR	5.6ab	4.6b	1.03c	0.36cb	2.60b	0.53b	0.05bc	5.73ab	16.3c	1.43
L4 MPR	5.7a	4.7a	0.53d	0.23c	3.40a	0.73a	0.05bc	6.20a	13.8c	1.50
CV %	4.6	3.5	14.3	22.0	9.5	17.4	24.0	6.5	10.0	3.3

Any two means not followed by the same letter down a column are significantly different at P = 0.05

Table e. Effects of combining Tithonia green manure, MPR and different rates of limestone on selected soil properties

	pHw	pHKCl	Al	H	Ca	Mg cmol (+) kg ⁻¹	K	CEC	Bray I P	OC
									mg kg ⁻¹	%
LO	5.1c	4.1d	2.83a	1.73a	1.06d	0.30bc	0.07b	5.23c	9.2d	1.46
LO tithonia MPR	5.1c	4.3c	2.36b	0.63b	1.53cd	0.23c	0.14a	5.76b	31.9a	1.56
L1 tithonia MPR	5.3bc	4.3c	2.16b	0.53b	1.66c	0.33bc	0.13a	6.06ab	24.7b	1.56
L2 tithonia MPR	5.5b	4.5b	1.23c	0.46b	2.46b	0.46ab	0.13a	6.10ab	23.9b	1.56
L3 tithonia MPR	5.4ab	4.5b	1.10dc	0.43b	2.60ab	0.46ab	0.13a	6.13ab	21.5bc	1.56
L4 tithonia MPR	5.7a	4.7a	0.86d	0.23c	3.00a	0.60a	0.15a	6.46a	17.5c	1.53
CV %	4.3	4.1	10.6	15.8	13.0	24.6	11.9	2.5	11.2	3.9

Any two means not followed by the same letter down a column are significantly different at P = 0.05

Table f. Effects of combining Tephrosia green manure, MPR and different rates of limestone on selected soil properties

	pHw	pHKCl	Al	H	Ca	Mg cmol (+) kg ⁻¹	K	CEC	Bray I P	OC
									mg kg ⁻¹	%
LO	5.1d	4.1d	2.83a	1.73a	1.06e	0.30bc	0.07b	5.23b	9.2d	1.46
LO tephrosia MPR	5.2cd	4.1d	2.56a	0.90b	1.50de	0.13c	0.12a	5.43ab	28.8a	1.86
L1 tephrosia MPR	5.3bcd	4.2cd	2.00b	0.50bc	1.83cd	0.26bc	0.12a	5.50ab	22.4b	1.73
L2 tephrosia MPR	5.4bc	4.3bc	1.60bc	0.16c	2.20bc	0.46ab	0.13a	5.50ab	20.7b	1.66
L3 tephrosia MPR	5.5ab	4.5b	1.23c	0.13c	2.66b	0.53a	0.11a	5.86a	17.0c	1.63
L4 tephrosia MPR	5.7a	4.7a	0.46d	0.16c	3.33a	0.60a	0.14a	5.83a	14.5c	1.66
CV %	4.9	5.2	16.9	30.3	16.5	28.2	16.1	4.4	8.6	4.3

Any two means not followed by the same letter down a column are significantly different at P = 0.05

Appendix 2. Effects of limestone levels, GM and MPR addition on nutrient uptake in the greenhouse experiment

Table a. Effects of different levels of limestone on nutrients uptake

	DMY g/pot	N	P	K (mg/pot)	Ca	Mg	Zn µg/pot
L0	1.6b	21.9b	1.92c	25.6	10.4d	3.4c	656
L1	2.0ab	43.7a	2.60bc	30.7	16.0c	7.2b	381
L2	2.1ab	51.2a	3.27ab	33.4	19.1bc	8.5b	363
L3	2.5a	53.0a	3.65a	38.0	24.9a	15.3a	782
L4	2.5a	59.5a	3.20ab	35.3	23.8ab	14.6a	612
CV %	14.2	17.9	15.3	13.3	15.3	19.1	30.8

Any two means in the same column not followed by the same letter are significantly different at $P = 0.05$

Table b. Effects of a combination Tithonia green manure and limestone on nutrients uptake

	DMY g/pot	N	P	K (mg/pot)	Ca	Mg	Zn µg/pot
L0	1.6b	21.9b	1.92b	25.6c	10.4c	9.1d	65.6
L0 Tithonia	4.6a	124.6a	7.14a	66.1b	31.4ab	27.1c	148.3
L1 Tithonia	4.6a	132.2a	7.15a	71.0ab	35.6a	40.1b	162.6
L2 Tithonia	4.4a	127.0a	7.11a	69.6ab	28.9b	38.8b	138.9
L3 Tithonia	4.6a	134.2a	7.70a	63.8b	31.5ab	41.9b	152.1
L4 Tithonia	5.2a	151.5a	8.10a	82.7a	36.2a	49.2a	148.2
CV %	10.9	12.0	13.2	11.5	10.3	9.1	21.7

Any two means in the same column not followed by the same letter are significantly different at $P = 0.05$

Table c. Effects of a combination Tephrosia green manure and limestone on nutrients uptake

	DMY g/pot	N	P	K (mg/pot)	Ca	Mg	Zn µg/pot
L0	1.6b	21.9d	1.92d	25.6d	10.4d	9.1d	65.6
L0 Tephrosia	2.33c	56.0c	3.3c	35.0b	16.7c	16.7c	89.3
L1 Tephrosia	3.13b	80.8b	4.5b	48.8ab	25.7	27.8b	80.2
L2 Tephrosia	3.7ab	99.2a	5.0ab	48.8ab	34.1a	41.6a	99.7
L3 Tephrosia	3.8a	102.5a	5.9a	56.9a	33.6a	42.7a	74.9
L4 Tephrosia	3.9	101.8a	5.0ab	56.7a	37.1a	41.7a	65.8
CV %	11.1	10.4	12.8	17.4	13.4	15.4	24.6

Any two means in the same column not followed by the same letter are significantly different at $P = 0.05$

Table d. Effects of a combination MPR and limestone on nutrients uptake

	DMY g/pot	N	P	K (mg/pot)	Ca	Mg	Zn µg/pot
L0	1.6b	21.9c	1.92d	25.6b	10.4c	9.1c	65.6b
L0 MPR	4.2a	49.9b	5.55c	55.7a	31.8b	26.6b	150.1a
L1 MPR	4.2a	70.9a	6.08bc	60.8a	30.0b	27.7b	99.4ab
L2 MPR	4.3a	63.4ab	6.50abc	60.3a	31.3b	32.8a	92.7ab
L3 MPR	4.4a	76.3a	7.62a	54.3a	37.8a	37.3a	91.2ab
L4 MPR	4.4a	67.5ab	7.50ab	61.5a	34.2ab	37.4a	99.2ab
CV %	8.6a	17.8	13.1	19.3	11.1	9.1	30.8

Any two means in the same column not followed by the same letter are significantly different at $P = 0.05$

Table e. Effects of a combination Tithonia green manure, MPR and limestone on nutrients uptake

	DMY g/pot	N	P	K (mg/pot)	Ca	Mg	Zn µg/pot
L0	1.6c	21.9c	1.92d	25.6c	10.4d	9.1d	65.6c
L0 Tithonia MPR	8.1a	176.1b	15.35b	116.5ab	63.4b	60.6b	171.4b
L1 Tithonia MPR	8.4a	225.6a	17.82a	125.6a	72.2a	68.6a	338.2a
L2 Tithonia MPR	6.4b	175.0b	13.67bc	102.5b	56.5c	59.7bc	120.4bc
L3 Tithonia MPR	6.2b	162.1b	11.84c	97.7b	50.7c	56.9bc	187.5b
L4 Tithonia MPR	6.1b	157.8b	11.92c	97.1b	53.0c	56.4c	175.7b
CV %	3.5	10.1	10.9	10.9	6.8	4.0	24.5

Any two means in the same column not followed by the same letter are significantly different at $P = 0.05$

Table f. Effects of a combination Tephrosia green manure, MPR and limestone on nutrients uptake

	DMY g/pot	N	P	K (mg/pot)	Ca	Mg	Zn µg/pot
L0	1.6d	21.9	1.92d	25.6d	10.4d	9.1d	65.6c
L0 Tephrosia MPR	6.4a	142.9	10.50a	92.1ab	43.7ab	42.3bc	105.5bc
L1 Tephrosia MPR	6.4a	136.6	10.06ab	96.2a	50.5a	47.6ab	310.5a
L2 Tephrosia MPR	5.3b	109.5	10.44a	69.1c	42.7b	50.1a	138.8abc
L3 Tephrosia MPR	5.9ab	111.0	8.97b	72.7bc	50.6a	51.3a	258.5ab
L4 Tephrosia MPR	4.2c	98.1	6.72c	63.0c	29.4c	39.2c	128.7c
CV %	7.1	17.2	7.8	15.5	9.3	9.3	35.9

Any two means in the same column not followed by the same letter are significantly different at $P = 0.05$

Appendix 3. Mean monthly rainfall and temperature data (2001-2002) for

Tonga, Butare, Rwanda

Year/Month	Rainfall (mm)	Maximum temperature (°C)	Minimum temperature (°C)	Mean temperature (°C)
1. Year 2001				
October	151.0	24.7	13.5	19.1
November	295.0	24.0	13.3	18.7
December	63.0	24.4	13.0	18.7
2. Year 2002				
January	259.0	23.8	13.5	18.7
February	73.5	25.3	14.1	21.7
March	186.5	25.0	18.0	21.5
April	274.0	24.7	14.7	19.6
Total	1302.0			

Appendix 4. Some characteristics of soil profile analysis in Tonga

No	Horizon	W pH	KCl pH	— (%) —		— cmol (+) kg ⁻¹ —		Ca	Mg	K	CEC	Al	H	Total acidity	Brayl P mg kg ⁻¹	Clay	Silt	Sands
				OC	N													
1	0-17	4.9	4.4	0.17	0.12	1.2	0.6	0.08	8.1	3.1	0.8	3.9	7.5	29.6	16.0	54.4		
2	17-32	4.9	4.4	0.18	0.15	1.1	0.1	0.1	6.9	3.4	0.8	4.2	6.3	31.6	18.0	50.4		
3	32-82	4.6	4.3	0.07	0.13	1.5	0.1	0.04	6.0	2.9	0.7	3.6	2.9	25.6	18.0	56.4		
4	82-105	4.8	4.3	0.03	0.09	1.6	0.0	0.02	5.1	2.3	0.7	3.0	2.5	25.6	16.0	58.4		
5	105-	5.1	4.3	0.05	0.14	2.4	0.5	0.0	5.8	1.6	0.6	2.2	2.5	27.6	14.0	58.4		

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