INFLUENCE OF MINJINGU PHOSPHATE ROCK APPLICATION ON *TEPHROSIA VOGELII* FALLOW PRODUCTIVITY AND SUBSEQUENT MAIZE RESPONSE ON A FERRALSOL IN MOROGORO, TANZANIA

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ABSTRACT

The objectives of this study were to quantify the response of *T. vogelii* fallow to Minjingu Phosphate Rock (MPR) application at establishment on quantity and quality of biomass produced. P availability, total inorganic-N, maize yields, and pH and Ca changes on an acidic, P deficient Ferralsol. The data were collected from pot, incubation and field experiments. The pot studies were used to assess response of *T. vogelii* seedlings to MPR, P and Ca applications, and that of maize to *T. vogelii* biomass and MPR applications. Incubation experiments were used to evaluate the influence of MPR application on decomposition of *T. vogelii* biomass and N release, and the effects of combined application of MPR and *T. vogelii* biomass on Pi-P. The field experiments were used to evaluate the effects of MPR application at fallow establishment on *T. vogelii* performance, maize response to fallow biomass and MPR applications, and to residual MPR and fallow biomass and fresh biomass applications. In soil of pH 5.9, the quantity, quality and N_2-fixing capacity of *T. vogelii* seedlings were significantly improved relative to pH 5.0. Application of MPR improved these parameters at both values of soil reaction. The quality and quantity of *T. vogelii* biomass depended on P application. Combined application of *T. vogelii* biomass and MPR significantly increased maize DM yield in the pot and field studies, but depressed Pi-P in the incubation study. Decomposition of *T. vogelii* biomass was significantly increased only in the first 28 days by MPR application and was not effected thereafter. Minjingu PR application at fallow establishment significantly increased the quantity and quality of *T. vogelii* biomass, total inorganic-N and Pi-P in the fallows. Subsequent to fallows, application of *T. vogelii* fallow

biomass or combined with MPR significantly increased total inorganic-N. The Pi-P, earleaf N and P concentrations, soil pH, exchangeable Ca and maize yields were significantly increased by application of MPR at fallow establishment and by combined MPR with fallow biomass. It is concluded that application of MPR on a strongly acid P deficient Ferralsol improves the quantity and quality of *T. vogelii* fallows and subsequent maize yields.

DECLARATION

I, Chaboba Zaid Mkangwa, do hereby declare to the Senate of Sokoine University of Agriculture that this thesis is my original work and that it has never been submitted for a degree at any other University.

Signature ....

Chaboba Zaid Mkangwa

Date ...22/11/2004...

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DEDICATION

This thesis is dedicated to my parents the late Mzee Zaid Mkangwa and Bi Saada Shaje for morally laying down strong foundation of education during my childhood, and to my first wife the late Bi Aisha Baruani, who untimely passed away during proposal development for this study.

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$(NH_4)_2SO_4$	Ammonium sulphate
AAS	Atomic absorption spectrophotometry
AEC	Anion exchange capacity
Al	Aluminium
Al_2O_3	Aluminium oxide
ANOVA	Analysis of variance
B	Boron
Ca	Calcium
$CaCl_2$	Calcium chloride
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CEC	Cation exchange capacity
Co	Cobalt
CSP	Citrate soluble phosphorus
Cu	Copper
$CuSO_4$	Copper sulphate
CV	Coefficient of variation
cv	cultivar
dbh	diameter at breast height
DFB	Department of Forest Biology
DM	Dry matter
DMRT	Duncan's Multiple Range Test
DSP	Double super phosphate
DSS	Department of Soil Science
DTPA-TEA	Diethylene triamine pentaacetic acid-triethanolamine
EB	Exchangeable bases
ECEC	Effective CEC
FAO	Food and Agriculture Organization
Fe	Iron
Fe_2O_3	Ferric oxide

$FeCl_3$	Ferric chloride
FeO	Iron oxide
FYM	Farm Yard Manure
H	Hydrogen
H_2O	Water
H_2SO_4	Sulphuric acid
$HClO_4$	Perchloric acid
HF	Hydrogen fluoride
ICRAF	International Center for Research in Agroforestry
IF	Improved fallow
IFs	Improved fallows
IITA	International Institute of Tropical Agriculture
K	Potassium
K_2O	Potassium oxide
K_2SO_4	Potassium sulphate
KCl	Potassium chloride
m a.s.l.	meters above sea level
MAFS	Ministry of Agriculture and Food Security
Mg	Magnesium
MgO	Magnesium oxide
$MgSO_4$	Magnesium sulphate
Mn	Manganese
Mo	Molybdenum
MPR	Minjingu phosphate rock
N	Nitrogen
Na_2O	Sodium oxide
NAC	Neutral ammonium citrate
NaOH	Sodium hydroxide
NF	Natural fallow
NFs	Natural fallows
NH_4^+	Ammonium ion

NH_4OAc	Ammonium acetate
NO_3^-	Nitrate
NSS	National Soil Service
°C	Degrees celcius
OC	Organic carbon
OM	Organic matter
P	Phosphorus
P_2O_5	Phosphate
pH	Hydrogen ion concentration
Pi	Inorganic Phosphorus
Po	Organic Phosphorus
PR	Phosphate rock
PRs	Phosphate rocks
RAE	Relative agronomic effectiveness
RCBD	Randomized completely block design
RE	Residual effectiveness
rpm	revolutions per minute
SFI	Soil Fertility Initiative
SiO_2	Silicon dioxide
spp	species
SUA	Sokoine University of Agriculture
TMV-1	Tanzania maize variety one
TSBF	Tropical Soil Biology and Fertility
TSP	Triple super phosphate
UK	United Kingdom
USA	United States of America
USDA	United States Department of Agriculture
VAM	Vascular-arbuscular mycorrhiza
var	variety
WAE	weeks after emergence
Zn	Zinc

$ZnSO_4$	Zinc sulphate

CHAPTER ONE

1.0 INTRODUCTION

Soil fertility decline especially in N and P is a wide spread problem in Tanzania (Tanzania-SFI, 2000), and is among the major factors contributing to low maize yields in Eastern Tanzania (NSS, 1989). The major causes are inappropriate soil management practices including lack of fertilizer use. Low maize yields ranging from 900 to 1400 kg ha^{-1} (MAFS, 2002) and negative nutrient balances of 32 kg for N and 4.5 kg for P ha^{-1} yr^{-1} (Hartemink and Van Kekem, 1994) are some of the evidences of declining soil fertility in some areas of Eastern Tanzania.

Ferralsols accounting for 21% of arable land in Eastern Tanzania (De Pauw, 1984) support most of the agricultural activities (Mowo, 2000). These soils are characterized by low available nutrient reserves, high P fixation, toxicities of Al and Mn (if soil pH < 5.2), presence of low activity clays (Driessen and Dudal, 1991), and in cultivated lands, surface sealing and compaction (FAO, 2001). Due to these inherent unfavourable characteristics, Ferralsols cannot maintain high yields under continuous cropping without adequate soil fertility restoration coupled with appropriate soil management practices (Hartemink *et al.*, 1996). Long-term restoration and enhancement of soil fertility in Eastern Tanzania is therefore necessary if high crop yields are to be maintained.

Soil fertility improvement and consequently crop yields using inorganic fertilizers is an area that has received considerable research attention in Tanzania that led to the production of fertilizer recommendations for various crops (Mowo *et al.*, 1993). However, due to high costs, the adoption of inorganic fertilizers by small-scale farmers is low. Nyaki (1997) reported that about 15% of the households in Tanzania use inorganic fertilizers. According to Tanzania-SFI (2000), amounts applied are as low as 3.3 kg N, 1.9 kg P and 1.1 kg K ha^{-1}. The majority of the small-scale farmers thus rely on nutrients recycled through natural fallowing and progressively small amounts of crop residues, which do not provide adequate N and P levels for soil fertility restoration.

In Eastern Tanzania, natural fallowing in maize fields is practiced by 23% of small-scale farmers (Moshi *et al.*, 1997), and is a potential intervention even in locations with land shortage like Gairo (Mkangwa and Chilagane, 1994). However, natural fallows (NFs) require 8 to 10 years to restore soil fertility (Rocheleau *et al.*, 1988) to a level that can increase maize grain yields up to 3.2-5.9 t ha^{-1} (Hartemink *et al.*, 1996; Maroko *et al.*, 1999). Further, such long duration fallows are no longer a viable option of improving soil fertility because the demand for land has increased due to increasing population. Short duration, natural and unmanaged fallows of one to 6 years that are common in some maize growing areas in Eastern Tanzania (Moshi *et al.*, 1997) do not maintain soil fertility at levels similar to those achieved under long-duration NF (Aweto *et al.*, 1992). A shift to more permanent and sustainable food production systems that optimize nutrient cycling and maximize the use efficiency of minimal external inputs is thus required (Sanchez, 1994). One such system is the use of improved fallows (IFs) that can achieve the benefits of soil fertility replenishment of NF within a short time. In IFs, a tree, shrub, or herbaceous species grown in rotation with cultivated crops can achieve the soil fertility benefits within a shorter time (Prinz, 1986). The ideal plant species for IF systems should be fast growing, N_2-fixing and efficient at nutrient capture and cycling (Jama *et al.*, 1998).

Tephrosia vogelii Hook. f. is among suitable leguminous shrubs for enhancing soil fertility especially in IF situations (Hagedorn *et al.*, 1997). Substantial improvement of soil fertility and subsequent cereal yields ranging from 72 to over 100% relative to NF have been reported (Drechsel *et al.*, 1996; Kwesiga *et al.*, 1999). The advantages of *T. vogelii* over the other suitable leguminous species include: tolerance to periodic bush fires and periodic droughts occurring in the rainy season; its unpalatability to livestock (Rocheleau *et al.*, 1988; Kwesiga *et al.*, 1999); increasing available P in its rhizosphere (George *et al.*, 2002a); and relatively slow release of N from its biomass (Hagedorn *et al.*, 1997). Improved fallows of *T. vogelii* could thus improve soil fertility and hence maize yields in N and P deficient Ferralsols of Eastern Tanzania.

On soils with adequate levels of P, *T. vogelii* fallows could supply to the subsequent crop(s) sufficient N through increased biological N_2-fixation and subsequent N accumulated in its biomass (Hagedorn *et al.*, 1997). On the other hand, P mineralized in the soil and that accumulated in the biomass are normally inadequate even in situations where there are adequate P levels in the soil. Phosphorus accumulations ranging from 4-14 kg P ha^{-1} in *T. vogelii* biomass are common (Hagedorn *et al.*, 1997; Mgangamundo, 2000). This is equivalent to 5- to 17.5-% of recommended P rate of 80 kg ha^{-1} for optimum maize production in the Ferralsols of Eastern Tanzania. Thus, this species cannot optimize maize yield in these soils unless external P fertilizer is applied.

However, high cost of TSP limits its use. Minjingu phosphate rock (MPR), locally available in Tanzania, could be less costly alternative P source in Eastern Tanzania. Like other phosphate rocks, MPR has relatively higher residual effects than conventional P fertilizers (Semoka and Kalumuna, 1999; Mkangwa, 2003), but its low solubility limits its effectiveness especially in soils with pH > 6.0 (Mnkeni *et al.*, 1991). Industrial techniques to increase the solubility of P from PR are costly and alternative low cost approaches need to be tested. In P deficient Ferralsols, *T. vogelii* was shown to decrease organic P in the rhizosphere (George *et al.*, 2002a). Since *T. vogelii* plants appear to utilize organic P, its fallows may thus enhance P availability from MPR and may be among the low cost alternative approaches that have proved successful with species such as *Mucuna pruriens, Lablab purpureus, Vigna unguiculata* and *Cajanus cajan* with other PRs (Lyasse *et al.*, 2002; Vanlauwe *et al.*, 2002). If *T. vogelii* will exhibit similar responses to MPR as shown with other species, its utilization could be more economically viable and hence favour adoption of direct application of MPR in P-deficient Ferralsols of Eastern Tanzania.

However, before recommending the use of *T. vogelii* fallow with MPR on acidic and P deficient Ferralsols of Eastern Tanzania, a number of research issues need clarification. These include: (a) The extent of *T. vogelii* fallow productivity when treated with MPR at establishment on acid P deficient soils; (b) The influence of MPR applied at fallow establishment or combined with *T. vogelii* biomass on total inorganic-N, Pi-P, ear leaf N and P concentrations and maize yields; (c) The effect of MPR application to a P deficient Ferralsol on mass loss of *T. vogelii* biomass and N release; and (d) The extent of improvement of soil pH and exchangeable Ca as a result of MPR and *T. vogelii* biomass applications. The information generated from these studies under sub-humid conditions, could be extrapolated to other areas with similar soils and agro-ecological conditions in Eastern Tanzania.

General objective

The overall objective of this study was to investigate the response of *T. vogelii* fallow to MPR application at fallow establishment and the effects of combined application of *T. vogelii* biomass and MPR on soil fertility improvement on a Ferralsol at the Sokoine University of Agriculture (SUA) farm, Morogoro District, in Eastern Tanzania.

Specific objectives

The specific objectives of this study were:

(a) To evaluate the effects of treating acidic P deficient Ferralsols with MPR on quantity and quality of *T. vogelii* biomass;

(b) To identify the most limiting nutrient between P and Ca on *T. vogelii* performance;

(c) To assess the influence of MPR and *T. vogelii* biomass applications on P availability and its effect on maize ear leaf P concentrations and maize yields;

(d) To evaluate the effects of *T. vogelii* fallows and subsequent applications of MPR and *T. vogelii* biomass on total inorganic-, ear leaf N concentrations and maize yields;

(e) To monitor induced changes in soil pH and exchangeable Ca due to fallows, fertilizer use and maize cropping;

(f) To assess the suitability of using *T. vogelii* fallow combined with MPR for improving soil fertility in Ferralsols of Eastern Tanzania.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Ferralsols

Ferralsols are old red or yellow tropical soils developed on highly weathered and leached acid parent materials (Driessen and Dudal, 1991; FAO, 2001). These soils have diffuse horizon boundaries, a clay assemblage dominated by low activity clays (mainly kaolinite), a high content of sesquioxide and a Ferralic B horizon. A Ferralic B horizon is a subsurface horizon which has a texture that is sandy loam or finer and has at least 8% clay, at least 30 cm thick and has cation exchange capacity $\leq$ 16 cmol(+) kg^{-1} clay or has an effective cation exchange capacity of $\leq$ 12 cmol(+) kg^{-1} clay (Driessen and Dudal, 1991). Ferralsols in FAO soil classification correspond to Oxisols in Soil Taxonomy (USA), Latosols (Brazil), Sols ferralitiques (France) and Lateritic soils and Ferralitic soils (Russia) (FAO, 2001).

2.1.1 Occurrence and distribution of Ferralsols

Ferralsols are mainly found in areas between 750 and 2300 m a.s.l. and distributed over a wide range of landscapes, ranging from strongly dissected uplands to flat or gently undulating plains in medium and high altitudes (FAO, 2001). The parent materials of most Ferralsols consist of pre-weathered, mostly transported materials of old age, derived from a wide variety of rocks. The common parent materials for most Ferralsols in Tanzania include granite, gneisses, schists, phyllites and acid volcanics (Mowo, 2000).

Worldwide, Ferralsols cover about 750 million hectares, and are mostly found in the humid tropics in South America, Africa and in the hot and humid climate with easily weathering basic rock, like in Southeast Asia (FAO, 2001). In Africa, Ferralsols are the third major soil group and occupies 14.3% of the land surface (Eswaran *et al.*, 1997). In Tanzania, Ferralsols occupy 13.4% of the land surface and are second to Cambisols (39.7%) (Msanya *et al.*, 2002).

In Eastern Tanzania, comprising of Tanga, Morogoro, Dar es Salaam and Coast Regions, Ferralsols occupy about 21% of the land surface. Other major soil groups found in Eastern Tanzania are Xerosols (30%), Luvisols (16%), Regosols (7%), Vertisols (5%) and Cambisols (4%) (De Pauw, 1984). The distribution of Ferralsols in Eastern Tanzania is based on the reconnaissance map of De Pauw (1984). In Tanga Region, Ferralsols are in North, South and West of Tanga Municipality, in the uplands north of Usambara Mountains and in the Central uplands in the triangle delimited by Muheza, Mombo and Handeni towns. In Morogoro Region, Ferralsols are widespread in Morogoro Municipality and in Kilosa District. In the Coast Region, Ferralsols are found in areas bordering Handeni District and around Mdaula sub towns. Ferralsols are not common in Dar es Salaam Region.

2.1.2 General characteristics of Ferralsols

Driessen and Dudal (1991) and FAO (2001) gave a detailed account of the morphological, mineralogical, hydrological, physical, biological and chemical characteristics of Ferralsols. Morphologically, Ferralsols are deep, usually several meters thick, with diffuse or gradual boundaries and highly weathered. They have a ferralic subsurface horizon, reddish or yellowish in colour, with weak macro-structure and strong microstructure, but friable consistence. Other morphological characteristics of Ferralsols are deep internal drainage and absence of conspicuous mottles.

The mineralogical characteristics of Ferralsols include relative accumulation of stable primary and secondary minerals, with quartz being the main primary mineral and clay assemblage dominated by kaolinite, geothite, hematite and gibbsite. Due to presence of micro aggregates, weak structure and kaolinitic type clay, the hydrological characteristics of most Ferralsols are strong water retention at permanent wilting point and low moisture storage at field capacity (FAO, 2001). Thus, Ferralsols have a narrower available water range than other soils. Sanchez (1976) reported that available water in Ferralsols from São Paulo, Puerto Rico and Minas Gerais was < 10%, while that in Ultisols from Puerto Rico, Inceptisol from Hawaii and Philippines and Vertisol from Puerto Rico was > 10%. In Ferralsols of SUA Farm in Morogoro Tanzania, Kaaya *et al.* (1994) reported that available water was 7.1% compared to 8.3% in the Luvisols, 10.6-11.4% in the Cambisols, 10.5-15.1% in Nitisols, and 10.2-15.4% in the Fluvisols. Consequently, inadequate moisture in Ferralsols occurring on crests or summits (0-2%) of gently undulating landscape (peneplains) which are common in Eastern Tanzania is due to their low moisture storage at field capacity. Long dry spells that occur sporadically during most rainy seasons further aggravate this moisture inadequacy.

Because of the low available water range of these soils, maize starts wilting after 6 days of dry spell (Sanchez, 1976).

The physical characteristics of the Ferralsols include stable micro aggregates, which account for excellent porosity, good permeability and favourable infiltration rates. Clayey Ferralsols with high contents of pH-dependent charge have stable soil structure due to bonding of opposite charges. Such properties favour adequate aeration, water infiltration and root penetration, which ultimately may favour crop production (Buol *et al.*, 1996).

Biologically, Ferralsols are characterized by intense termite activity, which partly account for the typical diffuse horizon boundaries in the profiles (FAO, 2001). Ferralsols are chemically poor in plant nutrients especially P, N and K as well as Ca, Mg, S and some micronutrients and are characterized by absence of weatherable minerals. Due to high sesquioxides contents in Ferralsols, cation retention by the mineral soil fraction is low, with cation exchange capacity of 3-4 cmol(+) kg^{-1} soil and $\leq$ 16 cmol(+) kg^{-1} clay in the Ferralic B-horizon (Driessen and Dudal, 1991). Consequently, they have a low capacity to provide nutrients to crops.

Ferralsols have high P fixation and may have Al toxicity (Driessen and Dudal, 1991; Buol *et al.*, 1996). Soluble Fe, Al and Mn, oxy-hydroxides of Fe and Al and kaolinites are responsible for P fixation in Ferralsols. When soil pH is < 5.2, soluble Fe, Al and Mn fix phosphate by rendering P insoluble and therefore unavailable for plant growth (Driessen and Dudal, 1991). According to Buol *et al.* (1996), the chemical reaction between soluble Fe and Al and di-phosphate ions would result into the formation of insoluble hydroxyl phosphates:

$$Al^{3+} + H_2PO_4^- \text{(soluble)} + 2H_2O \Leftrightarrow 2H^+ + Al(OH)_2 H_2PO_4 \text{(insoluble)} \ldots\ldots\ldots\ldots [1]$$

The distribution of P fixing soils in Africa is 35%, with 2.4, 5.8 and 26.8% for slight, moderate and high P fixation classes, respectively. The remaining 65% do not fix P (Eswaran *et al.*, 1997).

2.1.3 Nutrient contents in some Ferralsols of Eastern Tanzania

Nutrient contents of Ferralsols in Eastern Tanzania vary from one site to another, but generally the contents of N and P in many locations are low (Moberg *et al.*, 1982; Mkangwa, 1983; NSS, 1989; Kaaya *et al.*, 1994; Hartemink, 1995; MacKenzie *et al.*, 1997; Msanya and Maliondo, 1998). Examples of levels of some nutrient elements considered low in soils for crop production are 0.05-0.12% N, Bray-II P < 10 mg P kg^{-1} and < 4.0 cmol(+) Ca kg^{-1} soil (Landon, 1991).

Topsoil sample (0-20 cm depth) from Ferralsols around Morogoro municipality indicated that about 60% of the samples contained < 0.12% N, while all the samples contained Bray-II P of < 10 mg P kg^{-1} (Moberg *et al.*, 1982; Mkangwa, 1983; Kaaya *et al.*, 1994; MacKenzie *et al.*, 1997; Msanya and Maliondo, 1998). In Tanga Region, topsoil samples from Ferralsols at Mlingano and from a number of estates, contained < 0.12% N in 50% of the samples, while all samples had extractable P contents of < 10 mg P kg^{-1} (NSS, 1989; Hartemink, 1995; Mowo, 2000). Calcium and CEC levels in Ferralsols around Morogoro are from 0.9 to 3.25 and from 7.8 to 18.7 cmol(+) kg^{-1}, respectively (Moberg *et al.*, 1982; Mkangwa, 1983; Kaaya *et al.*, 1994; Hartemink, 1995; MacKenzie *et al.*, 1997; Msanya and Maliondo, 1998). In Ferralsols from Mlingano and a number of sisal estates in Tanga region, the Ca values are from 4.0 to 8.0 and CEC values from 2.9 to 12.3 cmol(+) kg^{-1} (Hartemink, 1995; Mowo, 2000).

2.1.4 Phosphorus fixation by Ferralsols in Eastern Tanzania

The few studies conducted in some sites of Eastern Tanzania indicate that P fixation by Ferralsols is appreciably higher than in other P fixing soils (Ikerra and Kalumuna, 1991; Assenga *et al.*, 1998; Mwakisimba, 1999). Ikerra and Kalumuna (1991) observed higher P adsorption maxima in a Ferralsol (477 μg P g^{-1}) than in a Luvisol (386 μg P g^{-1}) at Mlingano Tanga. Assenga *et al.* (1998) reported P adsorption maxima of 1090 for Rhodic Ferralsols and 1325 and 1392 μg P g^{-1}, for Haplic Ferralsols from Marikitanda and Mlesa, in Tanga region. Ferralsols from Mzumbe and Magadu locations in Morogoro, had adsorption maxima of 447 and 467 μg P g^{-1}, respectively (Mwakisimba, 1999). The adsorption maxima of other P fixing soils were 375 μg P g^{-1} for Lixisols of Mlingano and 408 μg P g^{-1} for Ultisols from the SUA farm close to the main gate of the main university campus. Soils with P fixing capacity of 100-500, 500-1000 and > 1000 μg P g^{-1} are classified as medium, high and very high in P fixation, respectively (Juo and

Fox, 1977). Accordingly, the Ferralsols of Eastern Tanzania have medium to very high P adsorption capacity. The high P fixation in Ferralsols may thus limit crop production, when other nutrient elements and moisture are not limiting.

2.1.5 Soil fertility management options in Ferralsols

The chemical limitations of the Ferralsols require management options that will increase, maintain and release sufficient nutrients in the current and in subsequent cropping. Management options like the use of inorganic- or organic fertilizers, liming, use of suitable fallow species and adequate fallow periods, intercropping and crop rotations have been reported to increase crop yields significantly (FAO, 2001; Kawamala *et al.*, 2003; Tumuhairwe and Rwakaikara-Silver, 1999). On Ferralsols with coconut-based systems in Pangani and Mkuranga Districts in Eastern Tanzania, Kawamala *et al.* (2003) reported that intercropping and crop rotations increased yield of cassava by 77-96%, maize by 69-86%, and cowpea by 152%. On N and P deficient Ferralsol at Kabanyolo Uganda, Tumuhairwe and Rwakaikara-Silver (1999) reported that maize grain yield was increased by 6-45% due to inorganic fertilizer application. Fertilizer selection and timing of fertilizer application are important in increasing nutrient availability (particularly P) on Ferralsols. Application of higher rates of slow-release PRs than that of DSP and TSP eliminates both P and Ca deficiency and raises soil pH (Mwendwa *et al.*, 1999; FAO, 2001).

Liming strongly acidic Ferralsols, increases soil pH and Ca supplies, reduces P fixation and Al and Mn toxicities (Sanchez, 1976). Liming rates raising pH to 5.5 are usually sufficient to prevent toxicities of Al and Mn (Pearson, 1975). The amount of lime to be applied is based on laboratory method suggested by Kamprath (1970), but should eventually be calibrated against crop responses from field experiments (Wild, 1988). Liming has turned some Ferralsols into highly productive soils in Brasilia, Brazil (North Carolina State University, 1973), in Llanos Orientales of Colombia (Spain *et al.*, 1975) and led to residual effects of > 6 years in São Paulo, Brazil (De Freitas and Van Rail, 1975). In Brasilia Brazil, liming at 4.0 t ha^{-1} increased maize grain yield by 2.4-fold, while in Llanos Orientales of Colombia liming at 0.5 t ha^{-1} increased cassava, upland rice and cowpea yields by 1.2, 1.6 and 1.8-fold, respectively (North Carolina State University, 1973; Spain *et al.*, 1975).

In Eastern Tanzania, Ferralsols supports a variety of crops namely sisal, maize, coconuts, sorghum, cassava, cotton, citrus, various grain legumes and pastures (De Pauw, 1984; Mowo, 2000). Maintenance of soil fertility in Eastern Tanzania is achieved mainly by crop-natural fallow-rotation on anticipation that during the fallow period, soil fertility will be sufficiently restored (Hartemink, 1995). However, 18 years of natural fallowing in sisal estates did not sufficiently improve Bray-I P, and organic carbon, but increased soil pH accompanied by a decrease in Al saturation and a slight increase in exchangeable Ca and K (Hartemink *et al.*, 1996). Use of improved fallow (IF) of 1-2 years old on the other hand, elsewhere, increased soil fertility and subsequent maize yield by 72 to > 150% (Drechsel *et al.*, 1996; Gichuru, 1991).

Maintaining soil fertility by either application of inorganic / organic fertilizers, or by introducing IF technology with suitable fallow species and adequate fallow periods would encourage intensive crop production in Ferralsols, which will lead to household food security and could alleviate poverty in Eastern Tanzania.

2.2 Improved Fallows

2.2.1 An overview of improved fallows

Fallow is defined as the resting of land from cropping, for one or more growing seasons, to allow the land to be colonized by secondary vegetation that may be grazed or left unused. The fallow period may range from one to over 20 years, though bush fallow systems of West and Central Africa have an average duration of 8 to 10 years (Rocheleau *et al.*, 1988; Sanchez, 1999). In Eastern Tanzania, fallow periods ranges from one to 6 years for maize production (Moshi *et al.*, 1997), and 10 to 18 years for sisal production (Hartemink *et al.*, 1996). Fallows can be subdivided into three categories namely natural (NF), enriched and IF.

Natural fallows are early succession stages of secondary vegetation after a cropping period (Uhl and Jordan, 1984). Enriched fallows (EF) are NFs where certain tree species are planted at low densities to produce high-value products such as fruits, medicines or high-grade timber that will provide economic benefits during the fallow period (Brookfield and Padoch, 1994). In Southeast Nigeria, farmers encourage species such as *Dactyladenia (Acioa) barteri*, *Alchornea cordifolia*, *Anthonata macrophylla*, *Crestis ferrugina*, *Dialum guineense* and *Harungana madagascariensis* in the NF (Kang *et al.*, 1990). In Latin America, farmers encourage certain economic and soil fertility improving indigenous trees such as *Stryphnodendron excelsum*, *Dalbergia tucurensis*, *Dipteryx panamensis*, *Vochysia ferruginea* and *Tabebuia rosea* (Montagnini and Sancho, 1990) In Kilosa and Mvomero Districts in Eastern Tanzania, farmers plant *Grevilea robusta*, *Tectona grandis* and *Senna siamea* in their NFs for timber, building poles and fuel wood supplies (Mkangwa and Chihongo, 1997). In semi-arid areas of Ethiopia, farmers retain *Faidherbia albida* in their farms, to improve soil fertility and water holding capacity, whereas *Acacia senegal* plants are left to grow in the crop fields for up to 16 years for restoration of soil fertility in Sudan (Gachene and Kimaru, 2003).

Improved fallow involves planting of fast growing, N_2-fixing and deep rooting leguminous trees / shrubs to enhance soil fertility by N_2-fixation over a shorter time, and ultimately increase yields of subsequent crop(s) (Rocheleau *et al.*, 1988; Sanchez, 1999). This purpose is achieved through manipulation of management operations such as choice of tree species, spacing, density, establishment and pruning. The major advantages of IFs are summarised in Table 1.

Table 1. Major advantages of improved fallows

Major advantages	Mechanisms involved	Reference(s)
1. Accumulation of nutrient stocks in fallow vegetation.	(a) N_2-fixation; (b) Deep soil N capture; (c) Reduced leaching; (d) Transformation of less available inorganic / organic P forms into readily plant available forms; (e) Relocation in soil profile.	Hartemink *et al.* (1996), ICRAF (1998), Maroko *et al.* (1999), Szott *et al.* (1999), George *et al.* (2002a).
2. Improved soil physical conditions.	(a) Improved soil aggregation, porosity and pore connectivity; (b) Reduced soil bulk density; (c) Break up hardpans / compacted soil horizons; (d) Reduce soil erosion.	Torquebiau and Kwesiga (1996), Amadalo *et al.* (2003).
3. Improved soil biological activities.	(a) Build up of soil micro fauna and microbial populations; (b) Build up of VAM and rhizobial populations.	Palm *et al.* (1997).
4. Reduced weed, insect and pathogen populations.	(a) Reduced weed populations; (b) Shifts in weed species; (c) Decreased viability of perennial weed rhizomes; (d) Decay of annual seed bank.	Gallagher *et al.* (1999), Kwesiga *et al.* (1999), Sanchez, (1999), Amadalo *et al.* (2003)

A suitable IF species is determined by its ability to adapt to environment-related factors (Dommergues, 1992), its nutrient restoration period and induced changes of soil chemical properties obtained in the fallow period (Wadsworth *et al.*, 1990; Kleinman *et al.*, 1996). Other factors that determine suitability of IF species are soil fertility benefits subsequent to fallows (Rao *et al.*, 1998), and responses to management practices (Kadiata *et al.*, 1997).

2.2.1.1 Adaptation of fallow species to environment-related factors

Environment related factors influencing adaptation of a fallow species include soil-, climatic- and biotic-factors (Dommergues, 1992). Soil acidity and nutrient deficiency are among the major soil factors influencing fallow species adaptation (Kadiata *et al.*, 1996).

(i) Soil acidity

Soil acidity *per se* is not the growth-limiting factor, but rather one or more secondary factors, which are pH dependent. Some of the pH dependent secondary factors that limit plant growth at low soil pH include toxicity of Al and Mn, high P fixation leading to low P availability and deficiencies of Ca and Mo, and depression of nitrification, nodulation and N_2- fixation due to low microbial activity (Mengel and Kirkby, 1982). Extreme acidity severely depresses the establishment and growth of N_2-fixing legumes. Soil acidity depressed N and biomass accumulation of *T. vogelii* and *C. cajan* in Rwanda (Drechsel *et al.*, 1996). The growth rate, nodule numbers and N_2-fixing potential of *Acacia auriculiformis, Albizia lebbeck, Gliricidia sepium, Leucaena diversifolia, L. leucocephala* cv K28 and cv K636, *Lonchocarpus sericeus, C. cajan, Crotalaria juncea* and *Tephrosia candida* were significantly depressed by soil acidity (pH 4.9) at IITA in Nigeria (Kadiata *et al.*, 1996). These observations suggest that sites with extreme soil acidity require management practices to increase soil pH before fallow establishment.

(ii) Nutrient deficiency

Nitrogen-fixing legumes are less adapted to soils with low fertility, especially low levels of P, Ca and Mg, various micronutrients including Cu, Mo, and B and toxicity of Al and Mn (Drechsel *et al.*, 1996). Phosphorus is essential in nodulation and N_2-fixation, and contributes to increased growth rate of legumes, while inadequate available P depresses nodulation, N_2-fixation and growth rate. According to Gibson *et al.* (1982), the nodules contain up to 3 times more P per unit DM than the roots. In Rwanda deficiencies of P and micronutrients such as Zn, Mo and B in Ferralsols limited N and biomass accumulation of *T. vogelii* (Drechsel *et al.*, 1996), while ground cover, DM production and N_2-fixation of *Crotalaria ochroleuca, M. pruriens, C. cajan* and *S. sesban* were depressed even at 40 kg P ha^{-1} (Balasubramanian and Sekayange, 1992). Depression of DM production and N_2-fixation of *Crotalaria ochroleuca, M. pruriens, C. cajan* and *S. sesban* even at 40 kg P ha^{-1} was probably due to other limitations which was not identified. Addition of 20 kg P ha^{-1} on a P-deficient soil stimulated nodulation and symbiotic N_2-fixation of three *G. sepium* provenances at Fashola in Southern Nigeria (Sanginga *et al.*, 1994). Phosphorus application on P-deficient Ferralsols significantly increased DM yield of *S. sesban* and *C. calothyrsus* at Ochinga farm in Western Kenya (Ndufa *et al.*, 1999). Nitrogen content of *P. vulgaris* was increased by 35% due to addition of P at 26 kg ha^{-1} on soils with pH ranging from 5.8-7.0 and available P (0.2-6.6 mg P kg^{-1}) (Giller *et al.*, 1998). Thus, in P deficient soils, an external P application is essential for optimum performance of fallow species.

High mineral N inhibits *Rhizobium* infection. N_2-fixation and growth of N_2-fixing legumes. Application of large quantities of fertilizer N inhibits N_2-fixation but low doses (less 30 kg N ha^{-1}) of fertilizer N can stimulate early growth of legumes and increase their overall N_2-fixation. Kadiata *et al.* (1997) reported that incorporation of green manure into the soil significantly ($P \leq 0.05$) depressed N_2-fixation by 19.1% in *G. sepium* and 20.6% in *L. leucocephala*. Large quantities of fertilizer N leads to decline in N_2-fixation because the fertilizer inhibits nitrogenous formation and reduce enzyme activity appreciably (Muller-Samann and Kotschi, 1994). Starter N fertilizer at low rate may be required during fallow establishment especially in N deficient soils.

(iii) Climatic factors

The climatic factors particularly extreme temperatures and long dry season adversely reduce N_2-fixation and overall performance of N_2-fixing legumes (Abebe, 1994; Kwesiga *et al.*, 1999). In semi-arid areas of Ethiopia, plant height and diameter at breast height (dbh) of *Acacia cyanophylla, A. nilotica, A. seyal, Prosopis juliflora* and *Cassia siamea* were significantly ($P \leq 0.05$) reduced during a long dry season (Abebe, 1994). In low and sporadic rainfall year, survival of *T. vogelii* declined from 91 at six months to 51% at one year after planting, but the survival rate was higher (over 60%) at one year after planting in high rainfall year (Kwesiga *et al.*, 1999). This observation suggests that fallow species should be established in areas with reliable rainfall distribution.

With regard to temperature, Hernandez-Ameta *et al.* (1989) reported a critical temperature of 32°C for nodules to function properly and 38°C for nodulation. However, differences exist between symbiotic systems in their ability to tolerate high (> 35°C) and low (< 25°C) temperatures (Gitonga *et al.*, 1989), suggesting that mean soil temperature of a site should be considered before establishment of fallow species.

(iv) Biotic factors

Insects, nematodes and bacterial pathogens directly affect the establishment and growth of N_2-fixing legumes. In a field study, nematode infection reduced specific N_2-fixation activity of groundnut by 64% (Gibson *et al.*, 1982). Stem borer infection significantly ($P \leq 0.05$) increased the mortality of *A. cyanophylla* in Ethiopia (Abebe, 1994). This indicates that for fallow species to give optimum outputs pests and diseases should be minimal.

2.2.1.2 Nutrients restoration period under improved fallows

Nutrients especially N restoration period in improved fallows determines the length of fallow period of a species. The N restoration period varies with rainfall, climate and soils. Data from long-term fallow plots and estimates of annual additions indicate that the time required for sufficient N restoration in improved fallows can be ≤ 2 years (Kleinman *et al.*, 1996; Wadsworth *et al.*, 1990). The rapid restoration of N stocks results from its accumulation in the growing vegetation and additions from N_2-fixation. Fallows will generally accumulate less N if biomass accumulation is retarded due to soil-, climatic- and biotic-factors (Aweto, 1981; Szott and Palm, 1996), and consequently will require much longer period for soil N restoration.

2.2.1.3 Changes in soil chemical properties during fallowing

The major induced soil chemical changes that take place under tree fallows include increases of labile pools of soil OM, N levels, exchangeable cations, extractable P and changes in soil pH (Rao *et al.*, 1998). Low levels of total N, exchangeable cations and soil organic carbon (OC) were significantly increased in Western Kenya, after 1-year fallows of *C. cajan* and *L. leucocephala* (Onim *et al.*, 1990). These parameters were also increased following 1-year *T. vogelii* fallow relative to grass fallow in Cameroon (Prinz, 1986), and in 1-, 2- and 3-year *T. vogelii* fallows in Gairo, Tanzania (Mgangamundo, 2000). In Nigeria on an Ultisol, 2-year-old *T. candida* fallows increased both OC and total N by 1.1-fold while *C. cajan* fallows increased both OC and total N by 1.2-fold over natural bush fallow in the 0-5 cm depth (Gichuru, 1991). The increase in OM, N levels, exchangeable cations and extractable P were attributed to their release from decomposing fallow biomass.

With regard to soil pH, the changes are variable with species, inherent soil properties and amount of biomass and sampling period. Topsoil pH decreased under the fallows of *A. auriculiformis*, *C. cajan* and *T. candida* (Drechsel *et al.*, 1991; Gichuru, 1991). The decrease in soil pH was associated with decrease of Ca levels in the soil due to plant uptake and leaching of cations (Montagnini and Sancho, 1990). The soil pH under newly established *L. leucocephala* and *Prosopis chilensis* was not affected (Jonsson *et al.*, 1996) possibly this was due to less plant Ca uptake. On the other hand, the soil pH subsequent to long term *T. vogelii*, *A. indica*, *S. siamea*, *Albizia spp*, *L. leucocephala*, *S. sesban* and *C. cajan* fallows was increased (Drechsel *et al.*, 1991; George *et al.*, 2002b; Onim *et al.*, 1990). These workers attributed the increase of soil pH to incorporation of biomass, which released substantial Ca levels in soil upon their decomposition.

In the lowlands of Costa Rica, significant soil improvements were observed under short- and long-term woodlot plantations, irrespective of whether the trees were N_2-fixing. The average increases in total N, Ca and P under 30-month-old stands of a number of indigenous trees were 1.3, 1.5 and 1.1-fold, respectively, relative to grass fallow (Montagnini and Sancho, 1990). Drechsel *et al.* (1991) observed improvement of 40 - 60% in OM, CEC and exchangeable cations in the 0-15 cm depth under five year old *A. auriculiformis*, *S. siamea* and *Albizia spp* and 115% increase in soil OM under *Azadirachta indica* compared with grass fallows. Montagnini and Sancho (1990), Drechsel *et al.* (1991) and Rao *et al.* (1998) argued that these increments were due to biomass decomposition and nutrient release from the above- and below-ground biomass and relocation of basic cations due to decomposing roots within the soil profile. The results shown above suggest a potential ameliorating effect of the leguminous fallow species on soil fertility, especially on soil pH, N and cations.

2.2.1.4 Responses to management practices

Management practices like pruning or lopping, intercropping, and wider spacing affect the performance of N_2-fixing plants. At IITA in Nigeria, Kadiata *et al.* (1997) reported higher (66%) average nodule number and dry weights in *L. leucocephala* and *G. sepium* that were not pruned than in pruned plants (47%). Intercropping legume and non-leguminous crops can result in competition for water and nutrients, which can lead to poor growth of N_2-fixing legumes. In the hills of Lao, Philippines, the initial plant population of *C. cajan* was reduced by > 10% at 15 months after planting by weed competition (Roder *et al.*, 1997). Delaying the sowing date, wider spacing of fallow plants, and early maturing and small stature variety reduce competition (Drechsel *et al.*, 1996), and hence increase N_2-fixation of N fixing plants.

2.2.1.5 Residual benefits of improved fallows

The residual benefit on subsequent crop yields is one of the main advantages of IFs. Research results from Rwanda, Kenya, Malawi and Zambia indicate that the residual benefits of IFs on crop yields occasionally lasts for three post fallow crops but is usually negligible after two crops (Drechsel *et al.*, 1996; Kwesiga *et al.*, 1999; Mafongoya and Dzowela, 1999; Amadalo *et al.*, 2003). In researcher-managed plots, fallow residual effects ranged from 40 to 170% in the first season and 42 to 84% in the second season, and decreased to 4 to 47% and to -3 to +27% in the third and fourth seasons, respectively (Drechsel *et at.*, 1996). In Malawi, Mafongoya. and Dzowela (1999) observed that relative to grass fallow, maize yield continued to increase in the third post-fallow of *Acacia angustissima*, *C. cajan* and *S. sesban* fallows. In Western Kenya, 18-months old *S. sesban* fallow produced in subsequent three seasons 9.7 t ha^{-1} of maize compared to 6.9 t ha^{-1} after grass fallow and 4.9 t ha^{-1} after continuous maize cropping. Such large residual effects are likely to compensate for the loss of production during the fallow period.

The residual benefits of IFs depend on the amount of biomass accumulated; the quality of fallow biomass and the rainfall in that growing season (Mafongoya and Dzowela, 1999). Species that produce high amounts of leaf biomass and litterfall normally give higher residual effects to crops (Schroth *et al.*, 1995). Mafongoya and Dzowela (1999) observed a highly significant correlation ($r = 0.92$) between *S. sesban* leaf biomass at the end of 1-, 2- and 3-year fallows and increase in grain yield of subsequent maize crop, compared to the maize yield following a NF. Regarding biomass quality, Barrios *et al.* (1997) observed that high quality biomass of fallow species led to more N in the soil OM light fractions, high pre-season soil inorganic N, and high aerobic N mineralization. Pre-season soil inorganic N at planting was directly correlated with maize grain yield following IFs (Barrios *et al.*, 1998; Maroko *et al.*, 1998).

2.2.2 Major disadvantages of improved fallows

The major disadvantages of improved fallows includes accumulation of large quantities of nutrients in woody parts of fallow species (Shepherd *et al.*, 1996), economic losses arising after loosing cropping season(s) during fallow establishment (Gachene *et al.*, 2000), and inadequate land availability (Drechsel *et al.*, 1996).

2.2.2.1 Quantities of nutrients in woody parts of fallow species

Improved fallows extract from soil various nutrients in large quantities and accumulate them in wood, which is not utilized in improving soil fertility. Wood products are frequently utilized as stakes, fuel and building materials and the nutrients contained therein are normally lost. Quantities of nutrients removed in wood products of IFs are of interest for the sustainability of this system (Shepherd *et al.*, 1996). Ndufa *et al.* (1999) observed that at 325 days after establishment, *S. sesban*, *Calliandra calothyrsus* Meissner and *G. robusta* accumulated 107-336 kg N ha^{-1}, 5.7-22 kg P ha^{-1} and 37-134 kg K ha^{-1}in woody products. After 17 months of *S. sesban* establishment, Maroko *et al.* (1999) reported that the amount of P removed in stakes was 9.0 kg P ha^{-1}. Mgangamundo (2000) observed that N content in the wood was 25.2 kg N ha^{-1} for 1 year-, 17.7 kg N ha^{-1} for 2 years- and 13.4 kg N ha^{-1} for 3 years-old *T. vogelii* fallows. In Western Kenya, George *et al.* (2002b) observed that stems of 12 months old *T. vogelii* plants accumulated 63.3% of total N accumulated in the biomass.

2.2.2.2 Economic benefits or losses during fallow establishment

The incorporation of IFs into cropping systems has high potential for sustaining soil fertility in the smallholder farming systems (Gachene *et al.*, 2000). The major disadvantage of this approach is that it requires a sacrifice of time, space and labour that could otherwise be used for cropping. However. economic assessments on IFs of *C. ochroleuca* and *S. sesban* suggest that the practice is economically attractive (Fischeler and Wortmann, 1999; Kwesiga *et al.*, 1999; Amadalo *et al.*, 2003). The net benefits for one season improved *C. ochroleuca* fallow and two subsequent cropping seasons were higher than for weedy fallow and two subsequent cropping seasons (Fischeler and Wortmann, 1999). In Eastern Zambia Kwesiga *et al.* (1999) conducted economic analyses for data from six - year on station experiment involving continuous unfertilised maize cropping, maize with recommended N fertilizer and 1-, 2-, and 3-year Sesbania fallows followed by continuous maize without fertilizer. Their study revealed that *S. sesban* fallows of 1- and 2-year generated 78- and 92-% more income, respectively than the control with the continuous unfertilized maize, while a 3-year fallow was marginally (2%) better than the control. The economic potential is greatest when returns to cropping are low, the opportunity cost of labour is high and where fallows provide valuable products such as fuel wood (Swinkles *et al.*, 1997).

Improved fallows treated with P at establishment can be more profitable than continuous cropping without P application or NF practices. Results from an on-farm trial in Western Kenya showed that returns to land and labour from a 7-9 months old *C. grahamiana* fallow to which 50 kg P ha^{-1} was applied, were 85 and 32.8%, respectively, relative to continuous cropping applied with same amount of P (Amadalo *et al.*, 2003).

2.2.2.3 Land availability

Land availability is among the major constraints of utilizing improved fallows especially in areas with very high population density and small farm sizes. In Rwanda Drechsel *et al.* (1996) reported that small farm sizes limit opportunities for utilizing improved fallows without loosing crop yields.

However, in areas with low population density as in some parts of Eastern Tanzania improved fallows could be a potential intervention in improving soil fertility and consequently crop yields. Research conducted in some maize growing areas in Eastern Tanzania indicated that natural fallowing is practiced by 23% of small-scale farmers (Moshi *et al.*, 1997). Similarly, in the sisal estates in Tanga Region, natural fallow of up to 18 years is common practice for improving soil fertility and subsequent sisal yields (Hartemink, 1995).

2.2.3 Relay cropping

Relay cropping involves growing of two or more crops simultaneously during part of each one's life cycle (Sanchez, 1976). In the context of improved fallow, it involves introducing a legume fallow species later after planting the main crop. The introduced legume fallow species remain in the field as fallow after harvesting the main crop.

Time of delayed planting of legume influences the yields of both species and N accumulation of relayed fallow species. At Kagasa Rwanda, Balasubramanian and

Sekayange (1992) observed that the DM yield of sole *C. ochroleuca* was 3.15 t ha^{-1} but was significantly ($P < 0.05$) reduced with time of relay planting from 0.17 t ha^{-1} at two weeks to 0.08 t ha^{-1} at four weeks. Nitrogen accumulation was also significantly ($P < 0.05$) reduced from 81.9 kg N ha^{-1} in sole *C. ochroleuca* to 4.3 and 2.1 kg N ha^{-1} at 2 and 4 weeks, respectively. Delayed planting for 5-6 weeks produced only 26-166 kg of DM ha^{-1}.

On marginal sites in terms of rainfall, delaying the sowing date of fallow species reduce competition for moisture and nutrients. However, because of short growing period of three months as the case of SUA farm, relay systems are risky. The relay systems are risky because the relayed fallow species may not receive adequate rains to withstand subsequent long dry season of 5-6 month.

2.2.4 *Tephrosia vogelii*

Tephrosia vogelii is a shrub that is well adapted to diverse climates and altitudes, produces high quality biomass, efficiently utilizes organic P and has high soil enrichment potentials. It is also easy to establish, tolerates drought, pests and diseases and is compatible with companion crops in rotational or intercropping systems (Milne-Redhead and Polhill, 1971; ICRAF, 1993; Gachene *et al.*, 2000; Amadalo *et al.*, 2003).

(intercropping) occurrence of food crops and a fallow species. Table 2 summarizes potential niches for *T. vogelii* fallows. This species can be planted as pure stand or by relay cropping and used for short (< 12 months) and medium-duration (14-24 months) improved fallows (Gachene *et al.*, 2000). Pure stand or relay cropping minimizes competition between the fallow species and the crop (Sanchez, 1995; Drechsel *et al.*, 1996) and hence increase their productivity.

2.2.4.4 Special attributes of *T. vogelii* biomass

Compared to the biomass of other species used in the IF technology, the biomass of *T. vogelii* has very peculiar characteristics. These include long-term effects of its green manure on yields of the following crop (Hagedorn *et al.*, 1997) and high contents of useful phyto-chemicals in its biomass (Lambert *et al.*, 1993; Morris, 1999).

(i) Long-term effect of *T. vogelii* green manure

The green manure of *T. vogelii* has long-term effects on soil fertility regeneration. Incubation studies have demonstrated that decomposition of *T. vogelii* biomass is relatively slower than that of *S. sesban* (Fasuluku, 1998; Palm *et al.*, 1988). Compared to *S. sesban* leaves with mass loss of 70% within the first 14 days (Palm *et al.*, 1988), the decomposition of *T. vogelii* leaves is relatively slower. Fasuluku (1998) reported that *T. vogelii* leaves released about 33% of N in its foliage in the first 7 days and 58% in first 28 days. Under field conditions, Hagedorn *et al.* (1997) observed consistently higher soil inorganic N in plots amended with *T. vogelii*

Table 2. Potential niches for *T. vogelii* fallows

Temporal niche	Spatial niche	Trade-offs (positive or negative effects)	Agro-ecozone
1. Relay cropping	Within any cropping systems e.g. cereal-legume as in small farms	Positive (a) Improved soil fertility; (b) Reduce soil erosion; (c) Reduce weed infestation. Negative (a) Lower yield of main crop	0-2300 m a.s.l. unimodal rainfall
2. Pure stand (short duration fallow, < 14 months)	Infertile patches and degraded soils and contours	Positive (a) Improved soil fertility; (b) Supply of staking material; (c) Reduce soil erosion; (d) Reduce weed infestation. Negative (a) Loss of crop in bimodal rainfall areas.	0-2300 m a.s.l. 500-2500 mm rain bimodal or unimodal rainfall
3. Pure stand (medium duration fallow, 12-24 months)	Hedgerow, contour strips, farm boundary and infertile patches. Medium to large farms	Positive (a) Improved soil fertility; (b) Supply of fuel wood; (c) Reduce soil erosion; (d) Reduce weed infestation; (c) Supply of staking material. Negative (a) Loss of crop in both bimodal and monomodal rainfall areas.	0-2300 m a.s.l. 500-2500 mm rain bimodal or unimodal rainfall

Sources: Rochleau *et al.* (1988), Drechsel *et al.* (1996), Kwesiga *et al.* (1999), Gachene *et al.* (2000).

biomass than in control and with plots of *S. bicolor* residues during the whole rainy season. The amount of N measured at 60 and 90 days after application of residues from *T. vogelii* were 52 and 42 kg N ha^{-1}, and were sufficient for sorghum and bean crops.

Hagedorn *et al.* (1997) attributed consistently higher soil inorganic N to the presence of phyto-chemical compounds contained in *T. vogelii* leaves which lead to slow N release, although Patnaik (1978) reported that biodegradation of toxic products of manures in soils took 7-10 days. The gradual nutrient release is a very useful attribute as the green manure from this species could contribute to the supply of nutrients for up to 3 post-fallow seasons (Amadalo *et al.*, 2003; Drechsel *et al.*, 1996 Kwesiga *et al.*, 1999; Mafongoya and Dzowela, 1999).

(ii) Useful phyto-chemicals

Tephrosia vogelii is among 17 known leguminous species with potentially useful phyto-chemicals (Morris, 1999). *Tephrosia vogelii* leaves contain rotenoid compounds, which include deguelin, rotenone, rotenolone and tephrosin (Lambert *et al.*, 1993; Morris, 1999). Rotenoid compounds have cyto-toxic effects and are used as insecticide, pesticide, piscicide, antifeedant and an acaricide (Morris, 1999). In West Africa, *T. vogelii* is traditionally used for its ichthyo-toxic, insecticidal and food parasiticidal properties (Lambert *et al*, 1993).

The extracts of *T. vogelii* leaves and roots are effective pesticides. In Pemba, Zanzibar Plant Protection Service uses the extract of *T. vogelii* leaves for control of Hispa (*Trichispa sericea*) on rice in farmer's fields (Fakih *et al.*, 2001). High concentrations ranging from 65 to 95% of leaf and root extracts of this species were fatal to rats (*Mastomys natalensis*) (Kassira 2001; Kejo, 2001).

2.2.4.5 Potential benefits of *T. vogelii* fallows in improving soil fertility

Tephrosia vogelii fallows can directly or indirectly ameliorate soil fertility problems. The benefits include N accumulation in its biomass (Balasubramanian and Sekayange, 1992; Drechsel *et al.*, 1996; Mgangamundo, 2000; Rutunga *et al.*, 1999), prolonged N supplies in the soil (Hagedorn *et al.*, 1997), increased supplies of P (George *et al.*, 2002a, 2002b) and other nutrients to crops (Drechsel *et al.*, 1996; Rutunga *et al.*, 1999). Others are improved soil physical properties and soil water retention (Torquebiau and Kwesiga, 1996), source of energy for soil micro-organisms (Palm *et al.*, 1997), suppression of weed (Kwesiga *et al.*, 1999) and supply of fuel wood (Sanchez, 1995).

(i) Nitrogen accumulation and its dynamics

Improved fallows of *T. vogelii* accumulate N through biological N_2-fixation, and through uptake from the soil, including deep nitrate capture. The N captured is accumulated in the biomass, which upon decomposition is released into the soil. *Tephrosia vogelii* can accumulate 150 to 240 kg N ha^{-1} in its biomass (Balasubramanian and Sekayange, 1992; Drechsel *et al.*, 1996; Rutunga *et al.*, 1999). In observation plots at Kagasa (soil pH-H_2O = 5.1), Rwanda, *T. vogelii* fallow accumulated dry weight equivalents of 4.8 t ha^{-1} of leaf litter and 2.6 t ha^{-1} of foliage, both adding 238 kg N ha^{-1} year^{-1} (Balasubramanian and Sekayange, 1992). On a Ferralsol in Southern Rwanda, Hagedorn *et al.* (1997) reported biomass production of *T. vogelii* relayed with sorghum of up to 6.6 t ha^{-1} that released 247 kg N ha^{-1}. In Western Kenya, 6-months old *T. vogelii* fallow, accumulated 9.5 t ha^{-1} of biomass which contained 154 kg N ha^{-1} (Rutunga *et al.*, 1999). Amadalo *et al.* (2003)

and Kamiri *et al.* (2001) in Western Kenya reported that 6-months-old *T. vogelii* fallow accumulated 173 kg N ha^{-1}, 58-73% of which was estimated to come from biological N_2-fixation. In Gairo, Tanzania Mgangamundo (2000) reported that *T. vogelii* accumulated 2.1-, 3.7- and 4.1-t ha^{-1} of foliar biomass which contained 54.4-, 79.2- and 77.4-kg N ha^{-1} in fallows at 1-, 2- and 3-years, respectively. In most cases, the N accumulated in the foliar biomass is sufficient for one to three subsequent maize crops, and could lead to doubling or quadrupling of maize yields on farmer's fields in the first post-fallow season (Kwesiga *et al.*, 1999; Niang *et al.*, 1998).

Mineral and total N in topsoil may also increase due to *T. vogelii* fallows or use of its biomass. Hagedorn *et al.* (1997) reported that mineral N determined at 60 days after application of residues from *T. vogelii* in the topsoil (0-20 cm) was 52 kg N ha^{-1} and was decreased to 40 kg N ha^{-1} when sampled at 90 days. The corresponding mineral N levels in plots treated with sorghum residues were 35- and 25- kg N ha^{-1} for sampling collected at 60 and 90 days, respectively. The authors concluded that the levels of mineral N obtained from application of *T. vogelii* biomass were sufficient for sorghum and bean production during the rest of the wet period. At Gairo, Tanzania Mgangamundo (2000), reported higher total N in the topsoil (0-10 cm depth) collected after harvesting 1-, 2- and 3-year-old *T. vogelii* than in NF plots. The total N levels were 0.19-, 0.21- and 0.21% for *T. vogelii* fallow plots compared to 0.096-, 0.077- and 0.065% for NF plots.

(ii) Phosphorus supply

In most studies with IFs of *T. vogelii*, P accumulations are low and are likely to have little or no benefit on soil extractable P. Phosphorus accumulations ranging from 6 to 15 kg ha^{-1} are reported in *T. vogelii* biomass weighing from 2.7-9.5 t ha^{-1} (Fasuluku, 1998; Hagedorn *et al.*, 1997; Rutunga *et al.*, 1999).

However, some IF species including *T. vogelii* increase pH and P availability in the rhizosphere (George *et al.*, 2002a, 2002b). Fallows of such species can increase the mineral P availability from soil organic P sources through association with vascular arbuscular mycorrhizae (VAM) (Bolan, 1991), altering pH (Gahoonia *et al.*, 1992), exuding organic acids (Kamh *et al.*, 1999) and phosphatase which catalyses the mineralization of organic P (Perez-Corona *et al.*, 1996). The extent of VAM infection on *T. vogelii* under field conditions is however low, ranging from 30-40% compared to 60-70% for *Tithonia diversifolia* (George *et al.*, 2002b), suggesting that its effect on organic P mineralization and P uptake is low. The rhizosphere pH of *T. vogelii* grown for 70 days in rhizopots and 18 months in the field was increased by up to 1-pH unit (George *et al.*, 2002a, 2002b). Concurrent with increase in rhizosphere pH, George *et al.* (2002a) reported a large depletion of organic P and an increase in available P by 38% in the rhizopot study. In the low pH soil (4.5), increase in pH led to decrease in the concentration of NaOH-Pi and -Po, due to reduced solubility of Fe and Al, leading to release of sorbed or precipitated P (Shang *et al.*, 1992).

Acidification of rhizosphere by organic acid exudates is negligible in cereals. Petersen and Bottger (1991) reported that such exudates contribute < 0.5% of the acidification of the rhizosphere in maize. Nevertheless, some plant species including *L. albus* L. exude large quantities of organic acids (Gardener *et al.*, 1983). Gardener *et al.* (1983) observed that the exudation of citrate by *L. albus* L. into the rhizosphere could increase P availability by mobilizing P from sparingly soluble Fe and Al phosphates. Ae *et al.* (1990) found that *C. cajan* L. had strong ability to utilize Fe bound phosphates by exuding piscidic acid that chelated Fe and thereby releasing phosphates from Fe phosphates.

The production of enzymes in the rhizosphere is another important mechanism which catalyses the mineralization of organic P (George *et al.*, 2002a). The rhizosphere of *T. vogelii* produces phosphatase that mineralizes organic into mineral P (George *et al.*, 2002a). *Tephrosia vogelii* fallow of 18 months old had significantly ($P < 0.001$) higher phosphatase activity than either maize or natural fallow plots (George *et al.*, 2002b). Declining organic P was related to phosphatase activity ($R^2 = 0.65$, $P < 0.05$). Phosphorus deficiency enhances phosphatase release while P applications depress its release (Jones and Farrar, 1999).

The apparent increase in available P in plots planted with *T. vogelii* fallows and its biomass retained in the field, and the ability of this species to acquire P unavailable to maize through rhizosphere effects suggest that this species has potential to increase the availability of soil P to a subsequent maize crop. However, the level of P supplied from fallow biomass including *T. vogelii* and from soil is often insufficient to meet crop demands (Sanchez, 1995). The inability of fallow systems to meet the P requirements of crops highlights the need for external P fertilizer use, especially on P deficient soils to ensure efficient functioning of the system and realize high productivity of crops (Palm, 1995).

(iii) Supply of other nutrients

Apart from increasing N and P supplies, *T. vogelii* biomass accumulates substantial amounts of other essential elements (Hagedorn *et al.*, 1997; Rutunga *et al.*, 1999). This is achieved by retrieving nutrients from the subsoil, particularly mobile ions such as K, accumulating them in the biomass and recycling them through litter and biomass decomposition to subsequent crop(s). Drechsel *et al.* (1996) reported that 2-year *T. vogelii* fallows accumulated 79-90 kg K-, 58-98 kg Ca- and 9-13 kg Mg-ha^{-1}. *Tephrosia vogelii* fallow alleviated K deficiency in subsequent *S. bicolor* L. and *P. vulgaris* L. at Kagasa, Rwanda by releasing 30 kg K ha^{-1} (Hagedorn *et al.*, 1997). In Western Kenya, a 6-month old *T. vogelii* fallow accumulated 100 kg K-, 75 kg Ca- and 17 kg Mg-ha^{-1} in its biomass (Rutunga *et al.*, 1999).

(iv) Improvement of crop yields

The effect of *T. vogelii* fallows on subsequent crop yields can be dramatic. Substantial yield improvement of subsequent crops has been reported widely (Drechsel *et al.*, 1996;

Gichuru, 1991; Hagedorn *et al.*, 1997; Kwesiga *et al.*, 1999, Mgangamundo, 2000; Murwira *et al.*, 2002; Niang *et al.*, 1996)

In Nigeria, on N deficient Acrisols, Gichuru (1991) observed maize yield increase of 157% after a 2-year *Tephrosia* fallow relative to natural bush fallow. In Rwanda on a Ferralsol, maize and bean yields increased by 72 and 96%, respectively, after a 1-year *T. vogelii* fallow compared to the control (Drechsel *et al.*, 1996). In Western Kenya, Niang *et al.* (1996) observed that maize yields after 6-month *T. vogelii* fallows were higher (100%) than yields obtained under continuous maize (80%) and after NFs (33%). On a Ferralsol in Rwanda, Hagedorn *et al.* (1997) observed that sorghum and bean yields were significantly increased by *T. vogelii* biomass applied alone or in combination with farmyard manure compared to control. At Chipata Zambia on an Alfisol, Kwesiga *et al.* (1999) observed increase in maize yield of 2.8- and 3.3-t ha^{-1} following 1- and 2-year *T. vogelii* fallows respectively, compared to 1.1 t ha^{-1} in unfertilized fields. The residual effects of 1- and 2-year *T. vogelii* fallows produced maize yields equivalent to 2.0 and 2.3 t ha^{-1}, respectively.

At Gairo Tanzania on a Nitosol, maize grain yield increased from 1.61 t ha^{-1} in the NF plots to 4.8 t ha^{-1} in 1-year-old *T. vogelii* fallow (Mgangamundo, 2000). Murwira *et al.* (2002) reported that maize yield increase due to *T. vogelii* green manure relative to control was over 600%. The high crop yield responses obtained after *T. vogelii* fallows are due to high fertilizer equivalent value of 93% (Murwira *et al.*, 2002), and gradual nutrient release from its biomass (Hagedorn *et al.*, 1997).

However, cotton and cassava yields were not increased following a 1-year *T. vogelii* fallow in Ukiriguru, Tanzania, due to the poor performance and low biomass produced of 0.3 t ha^{-1} by *T. vogelii* fallows (Ngazi and Kapinga, 1998). Poor performance of *T. vogelii* plants was also reported in acid P deficient soils in Morogoro, Tanzania (A.G. Mugasha, Personal Communication).

(v) Other benefits of *T. vogelii* fallows

Tephrosia vogelii fallows provide other important products and services beyond replenishing nutrient elements, which are considered as indicators of the sustainability of the new practice, making its use more attractive (Amadalo *et al.*, 2003; Power, 1999). These benefits of *T. vogelii* fallows include provision of fuel wood (Sanchez, 1995) and stakes (Amadalo *et al.*, 2003), source of pesticides (Morris, 1999) and medicines (Drechsel *et al.*, 1996). Furthermore, *T. vogelii* plants reduce nutrient loses through leaching and increases relocation of nutrients in the soil profile.

Fuel wood is the main source of energy for cooking in the tropics (Leakey and Sanchez, 1997). Use of *T. vogelii* can reduce the need of gathering fuel wood from adjacent forests. Research conducted in the semi-arid highlands of Rwanda indicated that 12-month old *T. vogelii* fallows produced 4.5-9.5 t ha^{-1}, while the 18-month old fallow produced 12 t ha^{-1} of fuel wood (Balasubramanian and Sekayange, 1992). In the semi-arid areas of Central Tanzania, Mgangamundo (2000) reported that 1-, 2- and 3-year old fallows of *T. vogelii* accumulated 5.44, 8.29 and 8.95 t ha^{-1} of fuel wood, respectively. The amounts of fuel wood obtained from *T. vogelii* fallows are higher than annual average family requirements. A study conducted in Lushoto Tanzania, indicated that an average family uses about 5.0 t of fuel wood year^{-1} (Fleuret and Fleuret, 1978). The stems of *T. vogelii* are also used as stakes to support other plants such as climbing bean and tomato (Amadalo *et al.*, 2003).

Insect pests severely defoliate some N_2-fixing species used in IFs. These include *Mesoplatys spp* on *S. sesban* and aphids on *C. grahamiana* (Sanchez, 1999; Sileshi *et al.*, 2000). Farmers from Luero village in Western Kenya intercrop *T. vogelii*, which is an insect-repelling fallow species, with *C. grahamiana* and *S. sesban* fallows to reduce damage of defoliating beetles (Sanchez, 1999) and for repelling moles (Amadalo *et al.*, 2003). As medicinal plant, Drechsel *et al.* (1996) reported that 24% of the farmers in Rwanda planted *T. vogelii* because of its medicinal properties.

2.2.4.6 Limitations of utilising *T. vogelii* fallows

Utilization of *T. vogelii* as a fallow species may be limited by low P accumulated in its biomass (George *et al.*, 2002b), susceptibility to long dry season (Kwesiga *et al.*, 1999) and infestation by root-knot nematodes (*Meloidogyne spp*) (Amadalo *et al.*, 2003; Kamiri *et al.*, 2001).

(i) Inadequate P supplies

Generally, the level of P in many locations with Ferralsols in Eastern Tanzania (Hartemink, 1995; Kaaya *et al.*, 1994; MacKenzie *et al.*, 1997; Mkangwa, 1983; NSS, 1989) is often inadequate for IFs (Fasuluku, 1998; Hagedorn *et al.*, 1997; Maroko *et al.*, 1999; Rutunga *et al.*, 1999). Inadequate levels of available P limit N_2-fixation and growth of N_2-fixing tree species (Giller *et al.*, 1998; Luyindula and Haque, 1992; Sanginga *et al.*, 1994) and reduce crop yields in subsequent season(s). Thus, to maximize N_2-fixation and biomass production in IFs, P should be applied to leguminous fallow species at planting.

(ii) Susceptibility to drought

A long dry season affect the establishment, survival and growth of *T. vogelii* fallows (Kwesiga *et al.*, 1999). In low and sporadic rainfall season, *T. vogelii* survival declined from 91% at six to 51% at 12-months after planting, while in a high rainfall season, the survival at 12 months was significantly improved to over 60% (Kwesiga *et al.*, 1999). The low survival in low and sporadic rainfall season was possibly due to low rainfall received at establishment and growth of *T. vogelii* plants. Such low and sporadic rainfall led to inadequate moisture supply to the plant roots in the subsoil.

(iii) Root-knot nematodes

Root-knot nematodes *(Meloidogyne spp)* are very small, parasitic worms that may enter and live inside the roots of the plants used for IFs including *T. vogelii*, *T. candida* and *S.*

sesban (Amadalo *et al.*, 2003). The nematodes also affect a number of crops (Amadalo *et al.*, 2003; Gachene *et al.*, 2000; Gibson *et al.*, 1982; Kamiri *et al.*, 2001; Sasser, 1979). The roots of infested plants develop swellings like nodules that are not easily rubbed off and leaves of the affected plants may show symptoms similar to nutrient deficiencies. Root-knot nematodes prefer infecting nodules on roots thereby interfering with nodulation and reducing the specific N_2-fixation activity of the nodules (Gibson *et al.*, 1982).

2.3 Minjingu Phosphate Rock

2.3.1 Occurrence and mineralogy of MPR

Phosphate rocks (PR) differ widely and have types with diverse origins ranging from igneous, sedimentary to metamorphic origins and mineral composition. The sedimentary rocks originate from organic material deposited on the sea floor and interbedded with a variety of other rocks, usually limestones and shales (Collings, 1955). Phosphate rocks contain P-bearing minerals belonging to the apatite family, the commonest primary phosphate mineral in the soil system (Mokwunye and Bationo, 2002). The most significant commercial PR sources in the world are sedimentary deposits with a high P content (15 - 40% P_2O_5), accounting for about 81% of the total PR production in the world. Sedimentary apatites are used for direct application and for manufacture of soluble phosphatic fertilizers. Minjingu PR from Tanzania is of sedimentary origin (Schlüter, 1993).

Minjingu PR is mined from Minjingu phosphate deposit located at Minjingu village about 80 km from Arusha town in Northern Tanzania. The deposit with estimated PR reserves of 10 x 10^6 t and about 2.2 x 10^6 t of easily processed ore has been formed by reaction between rich P-bearing solutions, resulting after guano washing and the alkaline waters of Lake Manyara. The phosphate formation comprises of two-ore types: lower and upper units that differ in structure and consistency. Soft phosphate ore on a lower topographic position (lower unit) is friable and is suitable for direct application to acidic soils (Buresh *et al.*, 1997). The upper unit (upper topographic position) is composed of hard phosphate ore which is characterized by a high content of dissolved silica (25%) (Schlüter *et al.*, 2000).

The mineralogical composition of the soft ore varies but generally consists of calcium phosphate (70%), carbonates (10%), quartz and colloidal silica (5-7%) feldspar (3-5%) and clay mineral (7%). Other components include minor amounts of biotite, muscovite, amphiboles, pyroxenes, limonite, *etc.* with a total P_2O_5 content ranging from 24-31% (Schlüter, 1993). The principal components of MPR are francolites or carbonate flourapatite $[Ca_5(PO_4,CO_3)_3/F]$ (Schlüter *et al.*, 2000). The chemical composition of soft ore MPR ranges from 25.0-29.23-, 37.15-42.03-, 9.5-13.89-, 1.56-2.89-, 0.51-1.3-, 2.22-4.05-, 1.14-1.55-, 0.85-1.4-, and 6.1-% for P_2O_5, CaO, SiO_2, Al_2O_3, Fe_2O_3, MgO, K_2O, Na_2O and NAC soluble P_2O_5, respectively (Geomin, 1970; Szilas, 2002; van Kauwenbergh, 1985).

2.3.2 Reactivity of PR

The effectiveness of PR as a P source for crops depends on its reactivity in the soil solution. Leon *et al.* (1986) rated PRs giving P levels $\geq$ 2.4% in neutral ammonium citrate and relative agronomic effectiveness (RAE) > 85% as highly reactive and hence effective for direct application. Minjingu PR is highly reactive on the basis of its 2.45% solubility in neutral ammonium citrate (Mnkeni *et al.*, 1992), and RAE of 92% in glasshouse study and 107% for dry matter yield and 156% for grain yield in a field experiment (Semoka *et al.*, 1992).

Because of being sufficiently reactive in soils, direct MPR application has been reported to increase crop yields by 40 to > 100% (Mkangwa, 2003; Mowo, 2000; Mutuo *et al.*, 1999). On an Alfisol in Western Kenya Mutuo *et al.* (1999) reported that direct application of MPR increased maize grain yields by 140% compared to 157% with TSP application. In Tanga region, Mowo (2000) reported that maize yields were increased by 73 and 108% at Mzambarauni and by 45 and 81% at Mlingano due to applications of MPR and TSP, respectively. In semi-arid areas of Central Tanzania, Mkangwa (2003) reported that in good rainfall years, direct application of MPR increased maize yields by 40% at Gairo and groundnuts yields by 68% at Hombolo. The increases due to TSP application were 32% for maize and 80% for groundnuts. However, crop yields obtained by direct application of MPR are in most cases lower than those due to TSP, calling for an alternative approach(es) that can increase its effectiveness. The alternative approach should consider soil and plant factors that influence MPR effectiveness.

2.3.3 Soil factors influencing PR dissolution

Compared to conventional P fertilizers, the direct use of MPR is constrained by low dissolution, hence P release. Commercial techniques to increase the availability of P from PRs are costly and alternative low cost approaches are being tested. A number of soil factors that influence the rate of dissolution and hence P release from PR have been identified and include the chemical composition and particle size of PR, soil properties such as soil pH, moisture content and Ca and P concentrations (Khasawneh and Doll, 1978; Rajan *et al.*, 1996). Their role on PR dissolution is based on the following equation:

$$\underset{\text{(PR)}}{Ca_{10}(PO_4)_6F_2} + 12H^+ \Leftrightarrow 10Ca^{2+} + 6\,H_2PO_4^- + 2F^- \quad \ldots\ldots\ldots\ldots \quad [2]$$

From the law of mass action, the dissolution of PR in soil will be favoured under low soil pH, low concentration of P and low levels of Ca (Rajan *et al.*, 1996). Thus, the dissolution is favoured by gradients in pH, Ca and H_2PO_4 ions. The relatively low soil pH and low available P in the Ferralsols of Eastern Tanzania could be an asset for direct MPR application.

2.3.3.1 Soil pH

Soil pH is among the main soil factors that influence PR dissolution (Chien and Menon 1995). In order to be effective, even relatively reactive PRs require acidic soils, generally with pH < 5.5 (Rajan *et al.*, 1996; Sanchez, 1976). Shinde *et al.* (1978) found that dissolution of both North Carolina and Gafsa PRs increased with decreasing soil pH. The dissolution of North Carolina PR was 41-, 30- and 5-%, while that of Gafsa PR was 71, 57 and 13%, at soil pH levels of 5.4, 5.9 and 6.4, respectively. Bolan and Hedley (1990) studied the effect of pH on the dissolution of North Carolina, Jordan and Nauru PRs, using a volcanic soil with pH ranging from 3.9-6.5. They reported that the amount of P dissolved from the PRs increased with decreasing soil pH. In a pot study carried out in Morogoro, Mnkeni *et al.* (1991) reported that the agronomic effectiveness of MPR was higher in acidic soils with pH < 5.2 than in soils with pH > 6.0.

2.3.3.2 Soil P

Soil soluble P levels commonly expressed by the activity of $H_2PO_4^-$ or by the phosphate potential (Khasawneh and Doll, 1978) play a great role in PR dissolution. Equation 2 shows that if the ionic product exceeds the solubility product of PR, the solubility of PR will not proceed, and to ensure PR dissolution continues, the soil solution should be low in $H_2PO_4^-$ (phosphate ions) (Sale and Mokwunye, 1993). Amberger (1978) reported that high PR dissolution is limited to soils with low to medium P status.

Robinson and Syers, (1991) reported that the extent of Gafsa PR dissolution was high in soil with very low solution P concentration of < 0.03 mmol dm^{-3}. Syers *et al.* (1992) reported that as Olsen extractable P in soils increased by 1.9, 3.5, 5.0 to 5.1 mg P kg^{-1}, the dissolution of Gafsa PR decreased in the order of 71-, 38-, 22- and 54-%, respectively. A sink for $H_2PO_4^-$ thus favours PR dissolution (Khasawneh and Doll, 1978). The agronomic effectiveness of PR therefore increases with a decrease in soil extractable P. Mnkeni *et al.* (1991) reported that, soils with low Bray-I P (P < 6.5 mg kg^{-1}) gave significant increase in maize yields while soils with high Bray-I P (P > 20 mg kg^{-1}) showed no response to P application from MRP.

Soil P sorption capacity also affects PR dissolution (Rajan *et al.*, 1996), with higher P sorption capacity causing greater dissolution by removing dissolved P from solution. Thus, although high P sorption capacity has generally been considered a liability hindering crop production (Sanchez and Uehara, 1980), a moderate sorption capacity may be considered beneficial by providing a reservoir of residual P available to subsequent crops (Sanchez *et al.*, 1997).

2.3.3.3 Soil Ca

Calcium concentration in the soil is among the important soil factors influencing PR dissolution (equation 2). The extent of dissolution depends on the level of Ca in the soil solution and the Ca sink in the soil. Low Ca concentration in the soil solution enhances PR dissolution (Khasawneh and Doll, 1978; Robinson and Syers, 1991). Hughes and Gilkes (1984) reported that the dissolution of Sechura PR increased as the exchangeable Ca decreased to < 1.5 cmol(+) kg^{-1} of soil. In contrast, dissolution of Gafsa PR decreased with increase in exchangeable Ca (Robinson and Syers, 1991). Soil affinity for Ca^{2+} promotes the dissolution of PRs because it provides a sink for the Ca^{2+} released.

2.3.4 Plant factors influencing PR dissolution

Plant related factors also influence dissolution and subsequent release of P from PRs (Khasawneh and Doll, 1978). Rajan *et al.* (1996) reported that plants could influence the rate of PR dissolution by: (a) Organic acids secreted by plant roots, that solubilize P from PRs; (b) High Ca uptake by some plants (*e.g.* legumes) increase the Ca sink; and (c) Chelating organic acids produced by roots (citric, malic, oxalic and 2-ketogluconic acids), complex Ca and P in the soil solution. Secretion of acids is high for legumes like *Pueraria japonica*, which secretes about 0.50 mM of acid per nM of N_2-fixed (De Swart and Van Diest, 1987). Nitrogen-fixing legumes acidify their rhizosphere through H^+ excretion by the plant roots to balance the excess cation uptake (Aguilar and van Diest, 1981). Chelating anions formed through the decomposition of the organic inputs may reduce P sorption by competing for adsorption sites, thus increasing P availability (Nziguheba *et al.*, 2002).

There are contradictory reports on the ability of OM to promote PR dissolution. Application of OM increased PR effectiveness (Rajan *et al.*, (1996), whereas Zaharah and Bah (1997) observed that application of OM increased effectiveness of less reactive PRs but decreased effectiveness of more reactive PRs. In a pot experiment using maize as test crop, Zaharah and Bah (1997) studied the effect of fresh leaves of *G. sepium, Acacia mangium, L. leucocephala* and *S. siamea* on P uptake by maize plants from North Carolina, Christmas Island, China, Algeria and Tunisia PRs, and found that, application of PRs alone significantly ($P \leq 0.01$) increased DM yield. Combined application of PRs with green manures modified the effect of the PRs on the DM yield from non-significant for reactive PRs to significant increases for less reactive PRs. Addition of green manures increased P uptake for less reactive PRs but decreased P uptake from more reactive PRs.

In the less reactive PRs, increased P uptake is associated with increased PR dissolution due to OM application. The formation of Ca-OM complexes which diminish Ca concentration in the soil solution, enhance PR dissolution (Chien and Menon 1995), while the formation of organic complexes (chelation) with released P decrease P fixation and serve as a slow release P source (Khasawneh and Doll, 1978). Organic acids produced from decomposed roots, root exudates and plant biomass are effective in releasing P from PRs (Iyamuremye *et al.*, 1996).

However, in Togo, Lyasse *et al.* (2002) found no significant effect of decomposing green manure of four species, on P availability from PR. Only 5.9% of the total P in maize could be attributed to the interaction between *Ricinus communis* green manure with PR in a multilocational field trial.

2.3.5 Agronomic effectiveness of MPR

Effectiveness of PR is often compared to that of soluble phosphate fertilisers like TSP or DSP. The relative agronomic effectiveness (RAE) of PR as described by Engelstad *et al.* (1974) is defined by the following formula:

RAE= 100 x Yield increase with PR / Yield increase with soluble P fertilizers ... [3]

Barrow (1980) and Sanchez and Uehara (1980) summarized several earlier studies and suggested that PR performance was inferior to that of TSP, but was superior to TSP in subsequent years though in many cases PR treatments never attained equivalent cumulative yields.

In a comprehensive review of PR research work conducted in Tanzania since the 1960s, Semoka and Kalumuna (1999) reported promising agronomic effectiveness of MPR. Under favourable conditions of low pH, P, Ca and high rainfall, MPR was as effective as conventional P fertilizers (TSP). In most cases, conventional P fertilizers were better than MPR in the first year of application but the effectiveness of MPR increased in subsequent seasons, with yields obtained from MRP applications in third year onwards being higher than those from conventional P fertilizers (Semoka and Kalumuna, 1999). In good rainfall years and favourable soil conditions, promising agronomic effectiveness of MPR was also observed in semi arid areas of Central Tanzania (Mkangwa, 2003).

2.3.6 Improving effectiveness of PR by P-efficient leguminous species

There is some evidence indicating that the availability of P from PR may be improved using P efficient leguminous species. The major mechanism involved is chelation of Fe^{3+} and Al^{3+} ions by root exudates (Ae *et al.*, 1990). Root exudates such as acetic, aconitic, citric, fumaric, glycolic, lactic, malic, oxalic and succinic acids play an important role in the mobilization of soil mineral nutrients like P, Fe, Zn, Cu and Mn

(Zhang *et al.*, 1997). Gardener *et al.* (1983) observed that the exudation of citrate by *L. albus* L. into the rhizosphere could increase P availability by mobilizing P from sparingly soluble Fe and Al phosphates. Ae *et al.* (1990) found that *C. cajan* L. had strong ability to utilize Fe bound phosphates by exuding piscidic acid that chelated Fe and thereby releasing phosphates from Fe phosphates. In a rhizopot study, George *et al.* (2002a) observed that *T. vogelii* rhizosphere depleted organic P through organic P mineralization in a strongly acidic, P deficient Ferralsol from Western Kenya. Declining organic P was related to phosphatase activity ($R^2 = 0.65$, $P < 0.05$). Phosphorus deficiency enhances phosphatase release while P applications depress its release (Jones and Farrar, 1999).

Hoffland (1992) concluded that secretions of organic acids is a highly effective strategy for increasing P uptake from PR. Some of the N_2-fixing legumes that are reported to improve P availability from PR include *L. leucocephala* and *G. sepium* (Mwendwa *et al.*, 1999), *S. seban* (Ndung'u and Okalebo, 1999; Njeri and Okalebo, 1999), *M. pruriens* and *L. purpureus* (Vanlauwe *et al.*, 2002) and *Vigna unguiculata* (Lyasse *et al.*, 2002).

In a pot experiment, Mwendwa *et al.* (1999) grew seedlings of *L. leucocephala* and *G. sepium* for 12 weeks on acidic (pH 4.8) and P limiting (6.3 mg kg^{-1}) soil collected from Wales in UK and treated with MPR. Plant height and shoot dry weight were significantly ($P \leq 0.05$) increased in all species by MPR application. In another pot study in Kenya, Ndung'u and Okalebo (1999) planted *S. sesban* on acidic (pH 4.5-5.0) Rhodic

Ferralsol with available P of 5.4 mg kg^{-1} for three months. Application of MPR significantly ($P < 0.05$) increased DM and P uptake of *S. sesban* but not N uptake. Njeri and Okalebo (1999) grew *S. sesban* in a pot experiment using a Ferralsol with pH 3.42-5.82, available P of 1.6-4.4 mg kg^{-1}, and MPR as a P source. Dry matter yield, N and P uptake, and enhanced N_2-fixation were significantly ($P < 0.05$) increased by MPR application. Increased MPR rates enhanced N_2-fixation by increasing effective nodule numbers. Thus, MPR appears to be an effective P source for growth of agroforestry leguminous trees / shrubs in acidic and P-limiting soils.

In the Northern Guinea savannah of Nigeria, Vanlauwe *et al.* (2002) assessed whether *M. pruriens* and *L. purpureus* were able to use P from PR on soils located along a representative toposequence. Addition of PR enhanced biomass production, N and P contents and seed production. In addition to the enhanced agronomic performance, the legumes also increased Olsen-P. Similarly, PR application enhanced arbuscular mycorrhizal fungi and rhizobium infection and nodulation.

This peculiar characteristic of N_2-fixing legumes to improve availability of P from PR is beneficial to less P-efficient crops grown in association like in rotational or relay cropping. Lyasse *et al.* (2002) assessed the ability of a *V. unguiculata*-maize rotation to enhance the availability of P from PR in Sekou, Benin. Phosphate rock application did not influence the agronomic performance of the legume in the first season, but increased subsequent yield of maize from 600 kg ha^{-1} in the control to 1000 kg ha^{-1} in plots treated with PR and planted with *V. unguiculata* in the first season. This implies that *V. unguiculata* enhanced the availability of P from PR without necessarily taking advantage of this PR itself.

2.3.7 Residual effectiveness of PRs

Mokwunye and Bationo (2002) defined the residual effectiveness (RE) of PR as follows:

RE-PR / RE-TSP x 100 .... [4]

where RE is residual effect of PR or TSP

Phosphate rock tends to persist in soils, sometimes for extended period. Khasawneh and Doll (1978) reported that some PRs persist for over forty years in some soils. The RE in soils previously amended with PRs increase with time of cultivation. In a glasshouse study, Kamasho *et al.* (1996) compared RE of MPR and TSP in six different soils from Mbozi District Tanzania, using maize as a test crop, and found that the RE of MPR increased from 74 to 87% for the first and second crops, respectively. In Togo, Mokwunye and Bationo (2002) assessed RE of one time application of Togo PR using maize as a test crop for two seasons, and observed increased RE from 91% in the first year to 111% in the second year.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Site Selection and Soil Characterization

Sites with Ferrasols were located in the SUA Farm using earlier soil survey reports (Moberg *et al.*, 1982; Kaaya *et al.*, 1994; Msanya and Maliondo 1998). Soil samples from the identified sites were collected at 0-20 cm depth and analysed for Bray-I P, total N and soil pH_{H2O}. A site with Bray-I P < 6.5 mg P kg^{-1}, deficient in N and pH_{H2O} < 6.0 was selected for these studies.

Prior to field experimentation, the soil classification of the selected site was confirmed by excavating a soil profile to a depth of 180 cm and the profile was described following standard guidelines (FAO, 1990). The profile description is given in Appendix 1. Exact location of the profile in terms of international co-ordinates was determined using a *Sony Global Positioning System Receiver*. Soil samples from this profile were taken from each horizon *ie* 0-20, 30-45, 60-90, 100-180 cm depths for laboratory analyses and the data is presented in Appendix 2. In addition, a representative composite soil sample of the experimental site was obtained from the plough layer (0-15 cm) for assessment of initial soil properties. Routine chemical and physical analyses of these soil samples were determined as described in sub-section 3.4.2. Using both field and laboratory data, the soil was classified up to level 3, *i.e.* soil unit names of the World Reference Base for Soil Resources (FAO, 1998) and up to the sub-group level of the USDA Soil Taxonomy System (Soil Survey Staff, 1999).

3.2 Physical Environment of the Study Area

3.2.1 Location

The field experiment was located at SUA Farm, about 5 km West of the centre of Morogoro municipality, Tanzania, at longitude 37°39'12.4" E and latitude 06°50'24.5" S, and at an elevation of 500 m a.s.l The slope of the experimental site was 1.5 to 2% and straight for over 200 m in a peneplain landform with gently undulating back slopes.

3.2.2 Geology

Uluguru Mountain is in the Southwest of the experimental site. Parent material of the experimental site is colluvium derived from mafic metarmorphic rocks (Fe and Mg containing rocks) originating from the Uluguru Mountains (Kesseba *et al.*, 1972). The Uluguru Mountains belong to the Precambrian Usagaran Geological System of the Mozambiquan Belt, with rocks that are essentially hornblende-pyroxene granulites containing plagioclase and quartz-rich veins (Moberg *et al.*, 1982). However, the chemical composition of the soil may be very different from that of original rock due to development of new minerals (Msanya, 2001).

3.2.3 Climate

The climate at SUA farm is tropical sub-humid. The 10-year mean rainfall data (1987/88-1996/97) indicate that the area experiences a bimodal rainfall distribution, with short rains normally from mid November to end of January. Long rains start between mid February and mid March ending in May. The onset and distribution is irregular and unreliable. In the 10-year period, the total annual rainfall ranged from 711 to 1044 mm with an average of 850 mm. In the same period, the monthly total evaporation varied from 74.3 mm in May to 176.9 mm in December. Moisture surpluses occur in the months of March to May, while for the remaining months of the year moisture deficits are experienced (Fig. 1).

During the 10-year period quoted above, the mean air temperature was lowest in June and July and highest in December to February. The mean monthly maximum air temperature ranged from 27.4 to 32.4°C, while the average monthly minimum air temperature was 15.5°C during the coldest months and 21.3°C in hottest months (Fig. 1).

3.2.4 Land use

The natural vegetation of the experimental site was miombo woodland, but was cleared during cultivation using a tractor for maize production and later establishment of the agroforestry experiments. The remnant natural vegetation in a few patches is dominated by grasses, mainly *Andropogon gayanus, Launaea conuta, Panicum maximum, Oxygonum sinuatum* and *Commelina beghalensis* and shrubs like *Senna obtusifolia* and *Lantana camara*. Currently, the land is used for agroforestry experiments. The main species tested include *G. sepium, L. leucocephala, Tamarindus indica, S. sesban, Acacia mangium, Albizia spp, Vitex spp* and *S. siamea*.

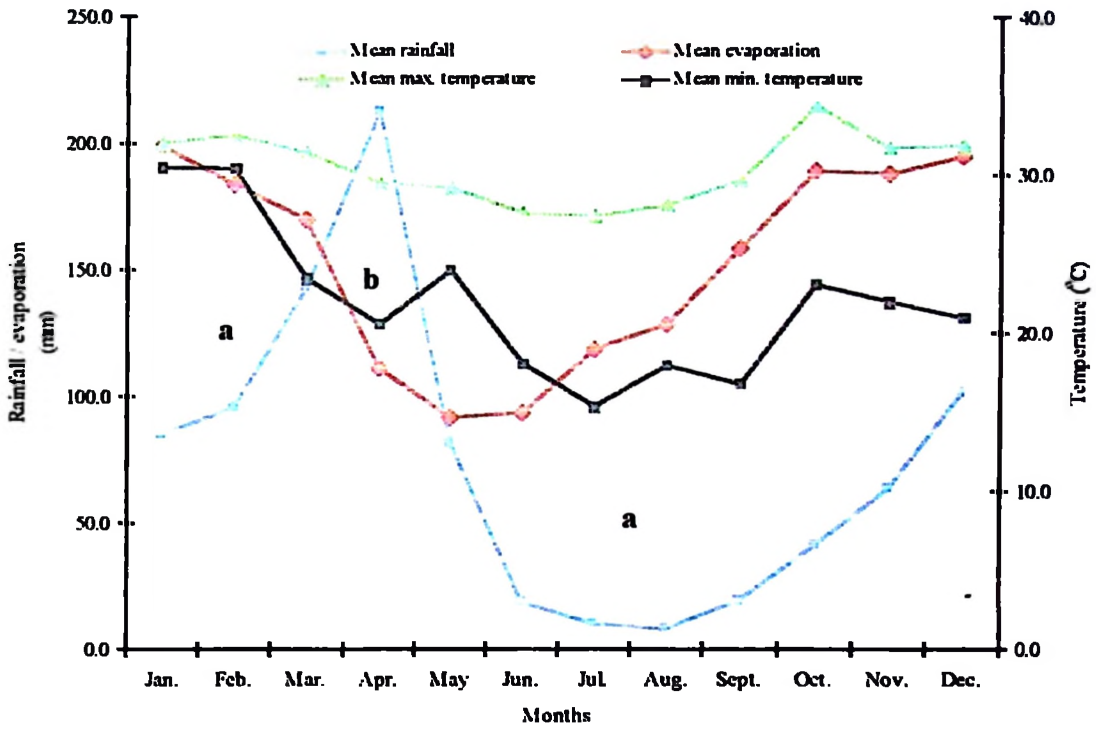


Figure 1. Ten year mean monthly rainfall distribution, evaporation, and mean maximum and minimum temperatures at SUA Farm, Morogoro, Tanzania.

Legend:

a Months with moisture deficits

b Months with moisture surplus

3.3 Characterization of Minjingu PR and *T. vogelii* biomass

Minjingu PR used in the incubation, pot and field studies was sub-sampled and analysed for total P, neutral ammonium citrate soluble P_2O_5, pH, $CaCO_3$-equivalent and CaO content. *Tephrosia vogelii* biomass was analysed for OC, total N, Total P, Ca and lignin.

3.4 Establishment of *T. vogelii* for Glasshouse and Incubation Studies

Tephrosia vogelii seeds were sown on 15 April 2000 at 50 x 50 cm spacing in a 0.25 ha plot for production of biomass for use in glasshouse and incubation studies.

3.5 Glasshouse Experiments

Three glasshouse experiments namely: Assessment of *T. vogelii* to MPR application on Ferralsols of different pH, *T. vogelii* response to P and Ca applications and maize (*Zea mays L.*) response to *T. vogelii* leaves co-applied with MPR were conducted on acid P deficient Ferralsol In order to obtain the soils with different pH levels, representative soil sample were collected from two sites. For each site, 10 sub-samples from 0-15 cm depth were mixed into a composite sample. Soil pH for soil-1 was 5.0 (strongly acid) and 5.9 (acid) for soil-2 Soil-1 was also used for the other two glasshouse experiments. The two soils were analysed for some chemical and physical properties using standard analytical methods as described in sub-section 3.8.2.

3.5.1 Response of *T. vogelii* to MPR application on Ferralsols of different Reaction

In this experiment, the assessment of *T. vogelii* to P at rates of 0 and 400 mg kg^{-1} applied as MPR to two soils with pH 5.0 and 5.9 was studied. Four treatments namely (a) soil pH 5.0 without P, (b) soil pH 5.0 with 400 mg P kg^{-1}, (c) soil pH 5.9 without P, and (d) soil pH 5.9 with 400 mg P kg^{-1} were arranged in a completely randomized design with nine replications. The logic for the high P rate of 400 mg P kg^{-1} was to ensure that P was not limiting since the Ferralsols of Eastern Tanzania have medium to very high P adsorption capacity (500 to >1000 μg P g^{-1}) (Assenga *et al.*, 1998; Mwakisimba, 1999). Plastic pots of 5 kg capacity were filled with 5 kg air-dry soil sieved through 8 mm. Basal applications of K, Mg and Zn were made at the rate of 50-mg K as K_2SO_4, 25-mg Mg as $MgSO_4$ and 5-mg Zn as $ZnSO_4$ kg^{-1} soil. Also, a starter N dose as NH_4SO_4 of 20-mg N kg^{-1} was applied because the total N and OM levels of 1.2 and < 25.8 g kg^{-1}, respectively were low (Landon, 1991). The fertilizers were thoroughly mixed with soil by hand.

Soils were moistened to approximately 80% of the field capacity by weight. On the second day, five *T. vogelii* seeds were planted in each pot and the seedlings were thinned to two plants per pot one week after emergence (WAE). Soil moisture was maintained as described by Klute (1986) between 70-80% of the field capacity throughout the experiment. Plant height, nodule numbers and shoot and root DM yield data were obtained at 3, 6 and 12 WAE, by destructive sampling of 3 replications each time. At each sampling, shoots obtained by cutting the plants at 1.0 cm above the soil level were washed in distilled water to remove adhering soil particles. Root biomass was obtained by separating it from the soil particles by simultaneously splashing water on the soil-roots mixture and sieving through a 0.8 mm sieve (Anderson and Ingram, 1993). The fresh material was oven-dried at 70°C to constant weight, and its DM weight recorded. Nitrogen and P contents were analysed in the shoot samples collected at 12 WAE.

At 12-weeks, the relative capacity for active N_2-fixation of *T. vogelii* seedlings as influenced by soil pH and MPR application was assessed by examining the effectiveness of nodule in N_2-fixation Nodules were dissected into two parts using a razor blade and the tissue was examined using a hand lens for effectiveness in N_2-fixation. Using a high-powered camera, nodular tissue from each treatment was photographed. According to Alexander (1985), the degree of nodule effectiveness is based on the colour of its tissue. The nodule tissue of actively fixing N_2 is distinctly red or pink in colour because of the presence of an iron-containing substance called leghaemoglobin. As effective nodules age, the cells lose their leghaemoglobin and their nodular tissue become brown in colour (Wild, 1988). In contrast, nodule tissue of ineffective rhizobia has white or green pigmentations (Alexander, 1985).

3.5.2 *Tephrosia vogelii* response to P and Ca applications

Since phosphatic fertilizers especially MPR supply both P and Ca, a response to MPR application calls for a follow-up experiment to assess the effect of varying P and Ca levels on the performance of *T. vogelii* on a soil with pH 5.0. Thus, a study to ascertain whether the response of 12-week old *T. vogelii* seedlings was due to P, Ca or both was conducted. The experimental design, basal fertilizer applications, watering regime, planting and thinning procedures were performed as in the first glasshouse experiment. The different levels of P and Ca compared are given in Table 3. The basis of using lower rates of P and Ca was to avoid confounding the results with other elements contained in MPR, KH_2PO_4 and $CaSO_4$ if applied at high rate. *Tephrosia vogelii* seedlings were grown for 12 weeks after which they were harvested. Data collected at harvesting included plant height, shoot DM yield after drying fresh material, and shoot N, P and Ca concentrations determined from dried material.

Table 3. Phosphorus and Ca rates assessed for *T. vogelii* performance

Treatment No.	Nutrient sources		Rates of application (mg kg^{-1})	
	P	Ca	P	Ca
1	-	-	0	0
2	-	$CaSO_4$	0	436
3	KH_2PO_4	-	160	0
4	KH_2PO_4	$CaSO_4$	80	436
5	KH_2PO_4	$CaSO_4$	160	218
6	KH_2PO_4	$CaSO_4$	160	436
7	MPR	MPR	160	436

3.5.3 Maize response to combined application of *T. vogelii* leaves with MPR

This experiment evaluated the response of maize to applications of *T. vogelii* leaves and MPR using a soil with pH 5.0. The experimental design and procedures for basal fertilizer applications and watering regime were performed as described in the first pot experiment (subsection 3.5.1). The sources and amounts of N and P applied are shown in Table 4.

Tephrosia vogelii leaves were ground to pass through a 0.5 mm mesh sieve before incorporation. Sulphate of ammonia was applied in two equal portions: the first at one day before planting and the second two weeks later. The other fertilisers were incorporated into the soil a day before planting. One day after fertiliser application, six maize (*Zea mays* L., var. TMV-1) seeds were planted in each pot. Maize seedlings were thinned to two plants per pot seven days later, and grown for 6 weeks. Maize plants were harvested at 6 WAE, by cutting at 2 cm above the soil surface using scissors, rinsed with distilled water, dried in an oven at 70° C to constant weight and weighed to obtain DM yield. Maize shoots were analyzed for N and P concentrations.

Table 4 Nitrogen and P sources assessed for maize performance

Treatment No	Nutrient sources		Rates of application (mg kg^{-1})	
	P	N	P	N
1.	-	-	0	0
2.	MPR	-	160	0
3.	MPR	$(NH_4)_2SO_4$	160	160
4.	TSP	$(NH_4)_2SO_4$	160	160
5.	*T. vogelii* biomass	*T. vogelii* biomass	9	160
6.	MPR	*T. vogelii* biomass	169	160

3.6 Incubation Studies

Two incubations studies using *T. vogelii* leaves and MPR were conducted. These were carried out to assess the influence of co-applying *T. vogelii* biomass with MPR on P availability, and the effect of MPR application on loss of mass of *T. vogelii* leaves and N release.

3.6.1 Effect of applying *T. vogelii* biomass and MPR on Pi-P

Phosphorus availability from MPR as influenced by *T. vogelii* biomass was assessed using 300 g of air-dry soil placed in plastic containers under non leaching conditions.

The treatments compared were (i) soil alone. (ii) soil + MPR, (iii) soil + *T. vogelii* biomass, and (iv) soil + MPR + *T. vogelii* biomass. The amounts of N and P added were equivalent to 80 kg N ha^{-1} from *T. vogelii* biomass and 80 kg P ha^{-1} from MPR. Distilled water was added to the mixtures to bring moisture content to about 80% of field capacity and was maintained at 70-80% by weight throughout the study period. The containers were arranged in a randomized block design, replicated four times. The incubated soil-MPR-*T. vogelii* biomass mixtures were aerated after thorough mixing using clean plastic spoon at room temperature once every other day and were sampled at 1-, 7-, 14-, 28-, 56-, and 84 days for determination of available P using the Pi method. Before each sampling, the mixture in each container was thoroughly mixed using a clean plastic spoon.

3.6.2 Influence of MPR application on decomposition of *T. vogelii* biomass and N release

The effect of MPR application on decomposition of *T. vogelii* biomass and N release on a Ferralsol was assessed using standard litterbags (30 x 30 cm with a mesh size of 7 mm) and incubation troughs using a procedure described by Anderson and Ingram (1993). *Tephrosia vogelii* biomass obtained from 12-month old plants were oven dried and amounts of biomass estimated to supply 80 mg N kg^{-1} were placed in the litterbags. The lower inside surfaces of the litterbags were lined with mosquito plastic net to decrease losses of undecomposed residues that could pass through the 7 mm mesh.

The incubation troughs were partitioned into four rectangular compartments as plots of 35 x 45 x 20 cm. Each plot was filled with 25 kg of the air-dried soil. Two P treatments, 0 or 80 kg P ha^{-1} as MPR were applied to the soil, and litterbags with *T. vogelii* biomass were buried at about 10 cm depth, moistened to 80% of field capacity, and incubated at room temperature for 0-, 2-, 4-, 8- or 12- weeks. The experiment was arranged in completely randomized design and replicated three times.

The 0-week incubation period represented the original weight and N concentration of *T. vogelii* biomass. In the remaining sampling times (2-, 4-, 8- or 12- weeks), three litterbags were retrieved from each treatment, and plant residues were oven dried at 70°C to constant weight and its weight recorded. The residues were then ground and analysed for N concentration.

3.7 Field Experiments

Four field experiments were conducted sequentially starting with establishment of fallows, first post-fallow maize response to fallow biomass, *T. vogelii* relay and second-post fallow maize response to *T. vogelii* relay biomass and to residual MPR applications. Table 5 gives the sequence of the activities in the field experiments and fertilizer types and rates applied.

3.7.1 Effect of MPR application on *T. vogelii* performance

The experiment on MPR application on *T. vogelii* performance, evaluated the influence of amending an acid P deficient Ferralsol with MPR and prevailing weather conditions on *T. vogelii* performance in terms of agronomic parameters, and quantity and quality of biomass produced under field conditions.

3.7.1.1 Land preparation and establishment of natural and *T. vogelii* fallows

The experimental field was ploughed using a tractor and the experiment was laid as randomized complete block design, replicated four times. The plot size was 4 x 8 m and the path between plots was 2 m wide. Three fallow systems namely natural, P unfertilized *T. vogelii* and P fertilized *T. vogelii* fallows at planting, were established and grown for 22 months. In order to improve tilth in the subsoil, holes measuring 20 x 20 cm and a depth of 30 cm at a spacing of 50 x 50 cm, were dug and then back filled starting with top soil. In plots amended with MPR, the soil from each hole was thoroughly mixed with MPR and then back filled.

On 15 April 2000, four seeds of *T. vogelii* were direct seeded at the centre of the back filled holes at 1-2 cm depth. Seedlings emerged after 3 to 5 days, and where necessary gap filling was done 7 days after planting. The seedlings were thinned to one plant per hill 14-days after first planting, leaving a plant population of 118 plants $plot^{-1}$ (equivalent to 37,000 plants ha^{-1}). In the natural fallow plots, natural vegetation regrowth was allowed to establish after cultivation.

3.7.1.2 Assessment of prevailing weather conditions

The effects of prevailing weather conditions were assessed in terms of rainy and dry seasons, hereafter referred to as wet and dry season, respectively. The wet season is from mid February-mid March to May and November to mid January, and dry season from June to October and late January to mid February (Fig. 1).

Table 5. Sequence of field experiments, fertilizer treatments and their schedule of application

Treatment	MPR vs *T. vogelii* performance (1999/00-2001/02)		First post-fallow-maize cropping (2001/02)			Second post-fallow-maize cropping (2002/03)			
	Fallow type	P applied[1] ($kg\ ha^{-1}$)	Fertilizer materials applied	N and P added ($kg\ ha^{-1}$)		*T. vogelii* relay status	Fertilizer materials applied	N and P added ($kg\ ha^{-1}$)	
				N	P			N	P
1	Natural fallow	0	Nf[2] biomass	25	2.4	Not relayed	Nf biomass	10	0.3
2	Natural fallow	0	SA	80	-	Not relayed	SA	30	-
3	Natural fallow	0	TSP+SA	80	80	Not relayed	SA	30	-
4	Natural fallow	0	MPR+SA	80	80	Not relayed	SA	30	-
5	*T. vogelii*	0	Tv[3] biomass	80	4	Not relayed	Residual Tv biomass	-	-
6	*T. vogelii*	80	Tv biomass	80	4	Not relayed	Residual Tv biomass	-	-
7	*T. vogelii*	0	Tv biomass+MPR	80	84	Not relayed	Residual Tv biomass	-	-
8	*T. vogelii*	0	Tv biomass	80	4	Relayed	Residual + fresh Tv biomass	30	1.5
9	*T. vogelii*	80	Tv biomass	80	84	Relayed	Residual Tv and MPR+ fresh Tv biomass	30	1.5
10	*T. vogelii*	0	Tv biomass+MPR	80	84	Relayed	Residual Tv and MPR+ fresh Tv biomass	30	1.5
11	Natural fallow	0	MPR+SA	80	80	Relayed	Residual Tv and MPR+ fresh Tv biomass	30	1.5
12	Natural fallow	0	Nf biomass	25	2.4	Relayed	Residual nf + fresh Tv biomass	30	1.5

[1]P source MPR
[2]Nf Natural fallow
[3]Tv *T. vogelii*

3.7.1.3 Management of fallows

Weeding in *T. vogelii* fallows was done at two-weeks and at 7- and 11-months. In order to stimulate more vegetative growth during the fallow period, *T. vogelii* flowers were removed. Natural fallow was allowed to grow without any management. Unfortunately, the 1999/00 long rains ended earlier than expected and was subsequently followed by a long dry season (Fig. 2). In a previous water budget study conducted in the SUA farm, it was shown that there is water deficit from early June to February in surface soils within a depth of < 40 cm (Isango, 1981). In order to ensure the seedlings survived during the 1999/00 long dry season, *T. vogelii* seedlings were watered at the rate of one litre plant^{-1} twice a week from mid August to late November 2000 when the short rains started. A firebreak of 3 m wide was established and maintained around the experiment throughout the experimental period.

3.7.1.4 Data collection in *T. vogelii* fallows

The data collected include plant population, plant height, root collar diameter, litterfall dry weight, foliar and stem biomass, and number of diseased *T. vogelii* plants. Nitrogen and P concentrations in the litter, leaves and stems were also determined.

The plant population of all the surviving *T. vogelii* plants in each plot were counted at 1-, 6-, 12-, 18- and at 22-months after planting and converted to survival percentages (%) of those initially planted. The plant height and root collar diameter were recorded when *T. vogelii* plants were 6-, 12-, 18- and 22-months old. The plant heights of the surviving *T. vogelii*

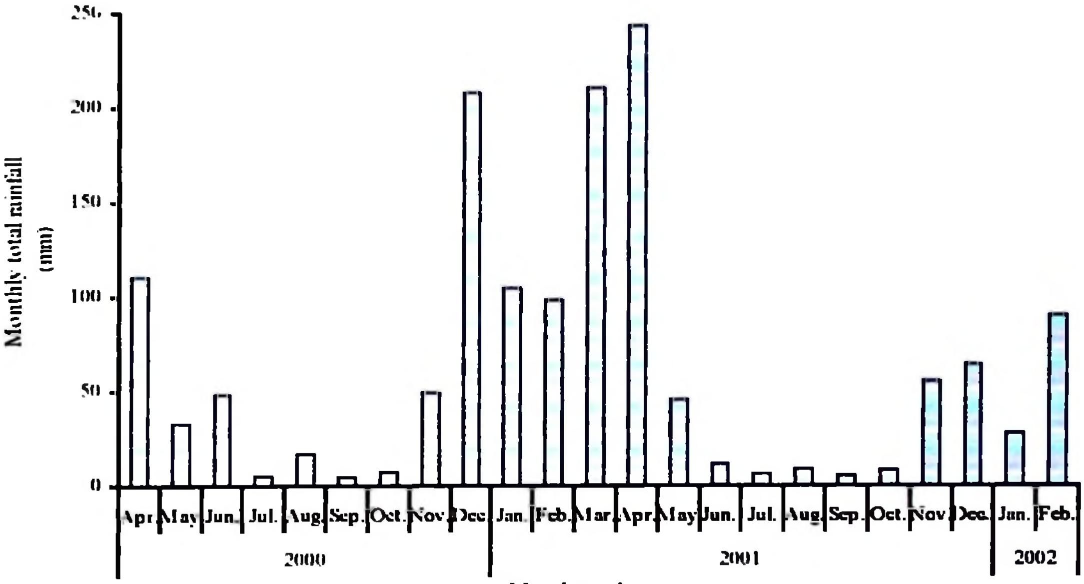


Figure 2. Rainfall distribution during 22 months of fallowing

plants in each plot were measured using a graduated pole. The root collar diameters of the surviving plants in a plot were measured using a vernier calliper whereby, for each plant, two measurements were taken perpendicular to each other and averaged at the height of 30cm from the ground.

Litterfall field weight was estimated by measuring all the litterfall collected in a 1 m^2 randomly selected quadrat in each plot. The quadrate was made of wood with 1 x 1 m dimension to avoid litter losses by wind. A portion of the litterfall was oven-dried at 70°C to constant weight, and used to calculate the dry weight on ha basis. The litterfall in the area outside the 1 m^2 quadrate was also removed, sun-dried and stored in jute bags. Litterfall was collected twice a month for 10 months, from 12- to 22-months. The total amount of litterfall in the 10 months period for each treatment was summed up from the individual collections.

Nitrogen and P concentrations were determined in litterfall and freshly sampled leaves. For litterfall samples, each 2-monthly litterfall collections were bulked, thoroughly mixed, and sub-sampled for N and P determinations. For leaf samples, four healthy *T. vogelii* plants outside the 1 m^2 quadrat were marked in each plot for foliar sampling. Recently matured leaves (two leaves below the tip) from top, middle and lower parts of the plants and branches near the tip of each branch were sampled, thoroughly mixed, oven-dried and ground. Leaf sampling was done when the plants were 6-, 12-, 18- and 22-months old.

Tephrosia vogelii plants were also examined for any disease infection. Diseased *T. vogelii* plants were counted and the number expressed as a percentage of those initially planted. Plant specimens of diseased plants were identified at the Plant Pathology Laboratory in the Department of Crop Science and Production. Diseased plants were counted at alternating dry and wet seasons, *i.e.* at 0-1 month in wet season, 2-6 months in dry season, 7-12 months in wet season, 13-18 months in dry season, and 19-22 months after establishment in wet season.

During the 22 months of fallowing, total inorganic-N and Pi-P were also monitored in the soil. For total inorganic-N assessments, soil samples were collected at 0-20 and 20-40 cm depths during the dry season (15 August 2001) and 3 days after the first rains of long rainy season (19 February 2002), whereas for determination of Pi-P, soil samples were collected only once at 3 days after the first rains.

At 22 months, the fallows were cleared for the first post-fallow maize cropping. *Tephrosia vogelii* plants were uprooted using hand hoes and roots were examined for any disease infection. The uprooted *T. vogelii* plants were divided into two components namely leaves and stems which included roots. The two plant components were separately weighed, sub-sampled, oven-dried at 70°C to constant weight, and used to calculate their dry weight on per ha basis. The oven-dried stems were ground for N and P determinations. The NF vegetation was also uprooted using hand hoes. The NF residues from each plot were also sun-dried and weighed and their portions were oven-dried at 70°C to constant weight and used to calculate the dry weights on per ha basis. The oven-dried residues were ground for N, P and Ca determinations.

3.7.2 First post-fallow maize cropping

3.7.2.1 Land preparation and treatments tested

At the beginning of the 2001/02 rainy season which was also the end of the fallow period, each plot was separately cultivated by using a hand hoe after uprooting *T. vogelii* plants and NF vegetation. The treatments evaluated in the 2001/02 season are given in Table 5 (page 70). Nitrogen from both S/A and *T. vogelii* biomass (equivalent to 4.6 t ha^{-1}) and P from TSP and MPR were applied at a rate of 80 kg ha^{-1}. *Tephrosia vogelii* biomass comprising of approximately 75% litter and 25% fresh foliar biomass was evenly spread and thoroughly incorporated into the soil by hand hoe 2 days before maize planting (28 February 2002). Residues from the NF plots were incorporated into the soil at a rate of 3.2 t ha^{-1} equivalent to 25 kg N ha^{-1}. Appendix 3 gives total amounts of Ca applied in the

T. vogelii biomass and NF residues. Both MPR and TSP were broadcasted because it was intended for both maize and *T. vogalii* relay and incorporated into the soil and was followed by maize planting on the same day.

3.7.2.2 Field operations and data collection

Maize (var TMV-1) was sown on 2 March 2002 at a spacing of 30 x 75 cm. Two weeks after planting, the plants were thinned to one plant / station giving a plant population of 137 plants plot^{-1} equivalent to 42,900 plants ha^{-1}. Sulphate of ammonia was applied in two equal portions, at 2 and 6 weeks after maize planting. The plots were weeded by hand hoe at 2- and 6-weeks after planting. Maize stalk borers observed on about 20% of maize plants at 4 WAE were effectively controlled by leaf extracts of *T. vogelii* obtained from 1:1 ground fresh leaf to water mixture.

On 30 March 2002, four seeds of *T. vogelii* were sown in treatments 8-12 (Table 5), as relay between the maize rows at 1-2 cm depth. Maize grain was harvested on 20 July 2002 from net plots measuring 2.5 x 7.40 m. Maize cobs were shelled, sun-dried to reduce the moisture content to approximately 12.5% and maize grain yield expressed as t ha^{-1} was recorded.

The data collected include total inorganic-N and Pi-P in the soil, N and P concentrations in ear leaves of maize plants and maize grain yield. Total inorganic-N was determined in the soils collected at 2, 35 and 45 days after planting, while Pi-P was analyzed in the soils collected only at 45 days after planting. The sampling dates corresponded to planting, vegetative and tasselling growth stages of maize plants. At each sampling, soil samples were collected from 10 locations $plot^{-1}$ at a depth of 0-15 cm, and bulked to obtain a representative composite sample. The ear leaves were sampled from 10 randomly selected plants $plot^{-1}$ at tasselling growth stage of maize plants. The leaf samples were cleaned using distilled water, oven-dried, ground and analysed for N and P concentrations.

3.7.3 *Tephrosia vogelii* relay experiment

3.7.3.1 Establishment and management of *T. vogelii* relay

Seeds of *T. vogelii* were directly sown between maize rows on 30 March 2002 at spacing of 60 x 75 cm and seedlings were thinned to one plant per hill, 2 weeks later giving a plant population of 71 plants $plot^{-1}$ (equivalent to 22,200 plants ha^{-1}). The relayed plants were weeded twice. The first weeding was at 2 weeks after sowing which coincided with the second weeding for maize and the second was at 8 months after planting. Maize harvesting was done on 20 July 2002, and thereafter all the stover was evenly spread in their respective plots without weighing. In order to stimulate more biomass production flowers were removed regularly. At 11 months, the plants were uprooted using hand hoe and land prepared again for the second post-fallow maize cropping.

The data collected in the relayed *T. vogelii* plants included survival, plant height, foliar and stem biomass and foliar N and P concentrations. The data for survival of relayed *T.*

vogelii plants were taken at 7- and 11-months after planting, plant height at 7- and 11-months, and biomass and foliar N and P concentrations at 11 months.

3.7.4 Second post-fallow maize cropping

The second post-fallow cropping assessed the response of maize subsequent to second application of *T. vogelii* biomass from the relays and to residual effects of MPR, TSP and *T. vogelii* biomass applied in the previous season(s).

3.7.4.1 Land preparation and fertilizer application

In the last week of February 2003, relayed *T. vogelii* plants and NF vegetation were uprooted and removed, and land was prepared as in the 2001/02 season. Both *T. vogelii* and NF biomass were sun-dried and weighed and their portions were oven-dried at 70°C to constant weight and used to calculate the dry weights on per ha basis. Due to slow growth during six months of dry season in 2001/02 season, the biomass accumulated by relayed *T. vogelii* plants was very low (Table 22), leading to incorporation of small biomass amounts equivalent to 30 kg N ha^{-1} in treatments 8-12. The extra N was obtained from biomass accumulated by *T. vogelii* plants established in 1999/00 (sub-section 3.4) near the experimental site. The same amount of N as S/A was applied in two equal portions in treatments 2-4. The NF residues were applied at an amount equivalent to 10 kg N ha^{-1}. Table 5 gives treatments tested in the 2002/03 season.

3.7.4.2 Field operations and data collection

Maize was sown on 14 March 2003 after incorporation of *T. vogelii* and NF biomass. Spacing and other field operations like thinning, weeding and control of stalk borers were performed as in the 2001/02 rainy season. Long dry spells between short rainfall events in the 2002/03 (Appendix 4) led to failure in grain formation, and this necessitated measuring DM as an index of maize yield. The rainfall distribution of 2002/03 season as compared to 10 year average is given in Fig. 3.

The data collected include total inorganic-N and Pi-P in the soil, N and P concentrations in ear leaves of maize plants and maize DM yield. Total inorganic-N were determined in the soils collected at 13 and 54 days after maize emergence, while Pi-P was analyzed in the soils collected only at 54 days after maize emergence. Soil and ear leaf samplings were performed as in the 2001/02 rainy season. The dry plant material was harvested in the net plots and its portion was oven-dried at 70°C to constant weight and used to calculate the DM yield on per ha basis.

3.7.5 Monitoring changes in soil pH and exchangeable Ca

The effects of fallows and different fertilizer treatments on changes in pH and in the supply of Ca were monitored in soil samples collected from 0-15 cm depth on 10 April 2000 and on 30 July 2003, representing the beginning and the end of the field experiments, respectively. Soil sampling was done by augering 10 locations in each plot,

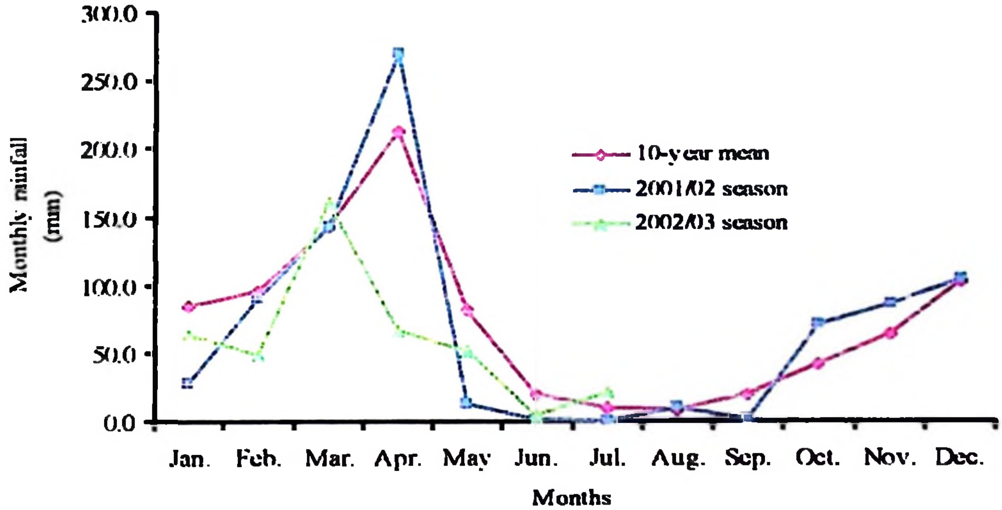


Figure 3. Monthly rainfall distribution during maize cropping and relayed *T. vogelii* experiments

which were composited and thoroughly mixed, then sub-sampled to obtain a representative composite soil sample that was measured for pH and exchangeable Ca.

3.8 Laboratory Work

3.8.1 Sample preparation

Soil samples for both physical and chemical analyses were air dried, ground and sieved through 2 mm sieve. Plant samples were oven dried at 70°C to constant weight, chopped into small pieces and finely ground using a micro mill to pass through 0.5 mm sieve.

3.8.2 Routine soil analyses

The characteristics determined in routine chemical analysis were soil pH, OC, available P, CEC, exchangeable bases, exchangeable Al, total acidity, total inorganic N, available

Cu and Zn and exchangeable Mn. Soil pH was measured in 1:2.5 soil-H_2O and soil-$CaCl_2$ suspensions (Thomas, 1996). Total N was determined by the macro-Kjeldahl digestion-distillation method (Bremner, 1996). Total inorganic-N was determined as described by Mulvaney (1996), whereby NO_3^-- and NH_4^+-N for each treatment were extracted separately. Total inorganic-N (NO_3+NH_4-N) values for each treatment from each sampling date were obtained by summation of NO_3+NH_4-N concentrations.

Organic carbon was analysed by the wet digestion method of Walkley-Black (Nelson and Sommers, 1996). Available P was determined by the Bray-I method (Kuo, 1996), and P in the extract measured colorimertically using the ascorbic acid molybdate blue method of Murphy and Riley (1962). The CEC and exchangeable bases were determined by the ammonium-saturation method (Sumner and Miller, 1996). Exchangeable Al and total acidity (Al+H) were determined in a soil-KCl extract (Bertsch and Bloom, 1996). Exchangeable Al in the extract was measured by AAS and total acidity by titration with NaOH. Diethylene triamine pentaacetic acid-triethanolamine (DTPA-TEA) was used to extract both available Cu and Zn (Reed and Martens, 1996). Manganese was extracted using DTPA-TEA as described by Gambrell (1996). The concentrations of Cu, Zn and Mn in the extracts were determined by AAS. Particle size distribution was determined by the hydrometer method after dispersing soil samples with sodium hexametaphosphate as described by Gee and Bauder (1996).

3.8.3 Determination of available P in P treated soils

Available P in soils treated with both organic and inorganic P fertilizers were determined using iron-oxide impregnated filter paper (Fe-O paper strip) method (Habib *et al.*, 1998). One g of an air-dried soil sample and an FeO paper strip (2 x 10 cm^2) were shaken with 40 ml of 0.02 *M* KCl for 16 hours using a reciprocating shaker at 150 rpm. The FeO paper strips were removed and gently rinsed with water to remove adhering soil particles The paper strips were air-dried and adsorbed P extracted with 40 ml 0.1 *M* H_2SO_4 for 1 hour using a reciprocating shaker at 100 rpm. The amount of P in the extract was determined colorimetrically using the ascorbic acid molybdate blue method of Murphy and Riley (1962).

3.8.4 Minjingu PR analysis

Minjingu PR was analysed for pH, total P, Neutral ammonium citrate soluble P_2O_5, and contents of $CaCO_3$ and CaO. The pH was measured in 1:2.5 MPR-H_2O mixtures (Thomas, 1996) and total P contents in the MPR were determined as described by Kuo (1996). Neutral ammonium citrate solubility of MPR was analysed as described by McMlellan and Gremillion (1980). Calcium carbonate was determined by acidification-titration procedure (Loeppert and Suarez, 1996), and its equivalency computed according to Tisdale *et al.* (1993). Calcium oxide content was determined by wet digestion method using HF-H_2SO_4-$HClO_4$ extraction (Hossner, 1996).

3.8.5 Plant analysis

The plant samples were analyzed for total N, OC, P, Ca, Mg, K and lignin contents. The total N was determined by the macro-Kjeldahl digestion-distillation method (Bremner, 1996). Plant OC was analysed by the Walkley-Black wet digestion method (Nelson and Sommers, 1996), while P, Ca, Mg, and K contents were determined after dry ashing of samples as described by Chapman and Pratt (1961) and lignin was determined using the procedure described by Van Soest *et al.* (1991).

3.9 Data Analysis

The data generated in experiments laid out in randomised block design, except for mass loss experiment, were subjected to analysis of variance (ANOVA). The mass loss experiment data for each retrieval time were converted to proportions of the mass and N contents that were applied and remained in the retrieved materials (Palm *et al.*, 1988), were analysed using student t-test. Total inorganic-N analysed was the sum of NH_4- and NO_3-N values at each sampling date. Soil pH and exchangeable Ca values at the beginning and the end of the experiments were compared using student-t test. The data obtained from experiments laid as RCBD were analysed using two-way ANOVA. All analyses were performed using software programs in the MSTAT-C statistical package. Significant treatment means were separated by Duncan's Multiple Range Test (DMRT) at 5% level of significance (Montgomery, 1991). Wherever applicable, simple correlation analyses were conducted to measure the relationship between yield and soil / plant factors contributing to that yield.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Soil Classification, Soil Properties and Soil Fertility Status of the Site

Some of the physical and chemical properties of the soil samples from the profile and of a composite sample of the experimental site are presented in Table 6 and profile description in Appendix 2. Table 7 gives some of the chemical and physical properties of the two soils (soil-1 and soil-2) sampled from the experimental site and used for glasshouse experiments.

4.1.1 Soil classification

The soil of the trial site at SUA Farm was classified by using both World Reference Base for Soil Resources (FAO, 1998) as Hyperdystri-Umbric Ferralsol and Typic Haplustox by USDA Soil Taxonomy (Soil Survey Staff, 1999) guidelines. The soils of the SUA Farm are developed on colluvium derived from mafic metamorphic rocks (Fe and Mg containing rocks) from the Uluguru Mountains, and have undergone substantial pedogenesis (Kesseba *et al.*, 1972; Msanya and Maliondo, 1998).

4.1.2 Soil properties

The initial status of soil properties such as pH, available P and exchangeable Ca are discussed because of their contribution to P availability from MPR and total N because of being the most limiting nutrient element in the tropics.

Table 6 Chemical properties of a composite soil sample from the experimental field

Parameter	Magnitude
Clay (%)	54
Silt (%)	10
Sand (%)	36
Texture class	C
pH H_2O (1:2.5)	5.06
pH KCl (1:2.5)	4.60
ESP (%)	1.18
Organic C (%)	1.3
Total N (%)	0.07
C / N ratio	18.6
Bray-I P (mg kg^{-1})	2.1
Pi - P (mg kg^{-1})	1.7
CEC NH_4OAc ($cmol_c$ kg^{-1})	15.2
Exch. Ca ($cmol_c$ kg^{-1})	4.4
Exch. Mg ($cmol_c$ kg^{-1})	2.3
Exch. K ($cmol_c$ kg^{-1})	0.68
Exch. Na ($cmol_c$ kg^{-1})	0.18
ECEC ($cmol_c$ kg^{-1})	6.88
TEB ($cmol_c$ kg^{-1})	7.56
Base saturation (%)	48.4
Exch. Al^{3+} (cmol kg^{-1})	0.01
Exch. H^+ (cmol kg^{-1})	0.11
Total Acidity (cmol kg^{-1})	0.12
Cu (mg kg^{-1})	1.13
Zn (mg kg^{-1})	0.63

Table 7. Some chemical and physical properties of the two soils used in the glasshouse studies

Properties	Soil-1	Soil-2
Soil pH (H_2O)	5.0	5.9
Soil pH ($CaCl_2$)	4.7	4.9
Total N (%)	0.07	0.07
OC (%)	1.3	1.16
P (mg kg^{-1})	2.5	2.9
Ca ($cmol_c$ kg^{-1})	3.0	3.9
Mg ($cmol_c$ kg^{-1})	1.63	1.60
Na ($cmol_c$ kg^{-1})	0.23	0.19
K ($cmol_c$ kg^{-1})	0.9	0.68
Exchangeable Al ($cmol_c$ kg^{-1})	0.19	0.03
Exchangeable H^+ ($cmol_c$ kg^{-1})	0.19	0.17
Total acidity ($cmol_c$ kg^{-1})	0.39	0.20
Exchangeable Mn (mg kg^{-1})	144.1	68.7
CEC ($cmol_c$ kg^{-1})	14.2	15.3
ECEC ($cmol_c$ kg^{-1})	4.86	5.69
Base saturation (%)	40.56	41.63
B (mg kg^{-1})	0.44	0.31
Cu (mg kg^{-1})	1.3	1.2
Zn (mg kg^{-1})	0.64	0.63
Sand (%)	36	34
Silt (%)	10	10
Clay (%)	54	56

The site had acid soil pH (H_2O) with surface soil horizon having pH of 4.8 and 5.1 in the composite soil sample. This low soil pH is desirable for increasing PR dissolution (Chien and Menon, 1995). The total N content in the surface soil was 0.12%, which would be rated as low. The total N levels rated as low range from 0.05 to 0.12% (Landon, 1991). The surface soil contained 1.43 mg P kg^{-1}, which is inadequate for most crops. However, low available P in soils increases dissolution and agronomic effectiveness of PRs (Amberger, 1978; Mnkeni *et al.*, 1991; Rajan *et al.*, 1996). The level of exchangeable Ca in the surface soil layer was within adequate levels. Response to Ca application for most crops is expected in soils with exchangeable Ca $<$ 0.2 cmol(+) kg^{-1} of soil (Landon, 1991).

The soil texture of the experimental site was clay. Previous studies (Msanya and Maliondo, 1998) indicated that the clay fraction in this soil was dominantly kaolinitic, containing 95% kaolinite, 1% gibbsite and 4% goethite, with clay mineralogy according to Moberg *et al.* (1982) composed of 38.03% SiO_2, 29.39% Al_2O_3 and 16.12% Fe_2O_3. In high P fixing soils, Mwakisimba (1999) observed that P adsorption was significantly correlated with Al_2O_3 ($r^2 = 0.79$) contents.

4.1.3 Soil fertility status

The soil fertility assessment of the experimental site was based on N and P contents. It was also based on OM contents because N and P availability to plants depends on a number of factors, including soil OM itself. For instance, soil N levels in the plant-available (NH_4^+ and NO_3^-) forms fluctuate during the cropping season and are dependent on factors such as soil moisture (rainfall pattern), cropping history, litter inputs and microbial activity. In case of P, crop responses to P is dependent on soil pH, with maximum P availability to plants in the pH range of 5.5-7.0, soil moisture content, P-sorbing capacity of soils and the clay contents. In this respect, a Nitosol at Gairo, Tanzania with Bray-I P of 3.7 mg kg^{-1} and known to be low in P sorbing capacity responded to P application rates as low as 15 kg P ha^{-1} (Mkangwa, 2003), whereas the Ferralsols at Kingolwira Tanzania, with high P-sorbing capacity responded to larger P rates of 60 kg P ha^{-1} (MacKenzie *et al.*, 1997). However, soils with total N levels < 0.12% and Bray-II P levels < 10 mg P kg^{-1} are regarded as being low in N and deficient in P (Landon, 1991).

Soil OM on the other hand, is not a requirement for plant growth, but its levels influence a number of chemical and physical processes in soils. According to Wild (1988), soil OM affects soil aggregates by binding individual clay particles into micro-aggregates, and improves soil moisture holding and cation exchange capacities. Mineralization of soil OM contributes to improvement of soil fertility through increased supplies of N, P, K, Ca, Mg and micronutrients. Due to these reasons, soil OM is a more reliable measure to indicate the status of soil fertility than other parameters. The soil fertility status of the site was rated as very low because the soil OM content in the composite sample was < 25.8g kg^{-1}. Landon (1991) categorized soil OM levels of < 25.8g kg^{-1} as very low.

4.1.4 Chemical composition of MPR and *T. vogelii* foliar biomass used

Table 8 gives selected chemical properties of MPR used. The MPR used contained 29.7% P_2O_5 and 50.1% CaO. The total P_2O_5 and CaO contents of MPR used are within the range reported by Szilas (2002).

The characteristics of *T. vogelii* leaves used in the incubation studies are given Table 9. Based on N content (3.4%) of *T. vogelii* biomass and lignin content (8.68%), the quality of the biomass was rated as high. High quality organic material contains > 2.5% N and < 15% lignin (Palm *et al.*, 1997).

Table 8. Selected chemical properties of MPR used

Parameter	Content
pH (water)	8.5
Total P_2O_5 (%)	29.7
Neutral ammonium citrate soluble P_2O_5 (%)	3.6
CaO (%)	50.1
$CaCO_3$ equivalent (%)	6.9

Table 9. Chemical composition of *T. vogelii* leaves used in the incubation and glasshouse studies

Parameter	Concentration
OC (%)	43.9
Total N (%)	3.4
Total P (%)	0.19
Ca (%)	1.3
Lignin	8.7
C:N	12.9
C:P	230.8
Ca:P	4.7
Lignin:N	2.6

4.2 Response of *T. vogelii* Plants to Soil Acidity and MPR Application

The response of *T. vogelii* plants to soil acidity and MPR application was assessed both under glasshouse and field conditions. Under glasshouse conditions, two studies were conducted, namely response of *T. vogelii* to MPR application on Ferralsols of different pH, and response of *T. vogelii* plants to P and Ca applications on a strongly acid P deficient Ferralsol

4.2.1 *Tephrosia vogelii* response to MPR application on Ferralsols of different Reaction

The objective of this study was to evaluate the response of *T. vogelii* to MPR applications on two acid P deficient Ferralsols differing in soil acidity, with soil-1 being strongly acidic (pH 5.0) and soil-2 moderately acidic (pH 5.9) (Table 7). The parameters used to assess *T. vogelii* response to MPR application included plant height, biomass yield, number of nodules, quality of *T. vogelii* biomass and relative capacity for active N_2-fixation.

4.2.1.1 Plant height

The influence of soil pH and MPR application on the height of *T. vogelii* seedlings at the age of 3, 6 and 12 weeks is given in Table 10. In soil of pH 5.0, plant heights were significantly lower at all the three sampling periods than in soil of pH 5.9. The relative shortness of *T. vogelii* seedlings at all the three sampling periods in soil of pH 5.0 was probably due to more severe acidity related constraints like higher Mn in this soil than in the soil of pH 5.9. Relatively better soil conditions, especially in relation to P and Ca and lower Mn concentration in the soil of pH 5.9 might account for the greater *T. vogelii* plant height observed (Table 10).

Application of MPR increased height of *T. vogelii* seedlings significantly at 3 and 6 weeks, but not at 12 weeks. At 12 weeks, plant height in the soil of pH 5.0 with MPR application was comparable to the height obtained in the soil of pH 5.9 without MPR application. Increase in P and Ca levels in the soil of pH 5.0 from MPR application could account for improved plant height of *T. vogelii* (Table 10).

Table 10. Effect of soil pH and MPR application on plant height of *T. vogelii*

Treatment	Plant height (cm)		
	3 WAE	6 WAE	12 WAE
Soil pH 5.0 without MPR	11.6 d	37.3 d	81.3 b
Soil pH 5.0 with MPR	15.6 c	44.7 c	93.0 b
Soil pH 5.9 without MPR	18.0 b	57.0 b	99.8 ab
Soil pH 5.9 with MPR	23.2 a	67.8 a	104.4 a

Means with the same letter within a column are not statistically different by DMRT at $P \leq 0.05$

Mwendwa *et al.* (1999) reported similar results with other nitrogen fixing trees. These workers found that the height of *L. leucocephala* seedlings increased at the rate of 1.44 cm week^{-1} in soil treated with MPR compared with 0.35 cm week^{-1} in the control. In the case of *G. sepium*, the rate of increase was 0.4 and 0.74 cm week^{-1} for control and MPR amended soils, respectively.

4.2.1.2 Biomass yield of *T. vogelii* seedlings

Table 11 gives the biomass yield reported as shoot and root dry matter yield of 3, 6 and 12 week old *T. vogelii* seedlings as influenced by soil pH and MPR application. Throughout the experimental period, shoot biomass was significantly lower in the soil of pH 5.0 than at pH 5.9, but root biomass in the two soils was statistically similar. Improvement in shoot biomass due to soil pH of 5.0 and 5.9 was 60% at 3 weeks, 213% at 6 weeks and 110% at 12 weeks.

Table 11. Effect of soil pH and MPR application on DM production of *T. vogelii*

Treatment	DM production (g pot^{-1})					
	3 WAE		6 WAE		12 WAE	
	Shoot	Root	Shoot	Root	Shoot	Root
Soil pH 5.0 without MPR	0.8 c	1.6 b	4.7 c	2.0 c	17.9 c	5.6 b
Soil pH 5.0 with MPR	1.2 b	1.9 a	8.9 bc	4.0 a	34.8 b	6.1 b
Soil pH 5.9 without MPR	1.2 b	1.4 b	14.8 ab	2.9 b	37.6 b	5.6 b
Soil pH 5.9 with MPR	1.8 a	2.0 a	23.1 a	3.9 a	51.3 a	7.2 a

Means with the same letter within a column are not statistically different by DMRT at $P \leq 0.05$

Application of MPR to both soils resulted in significant increases in shoot biomass at 3 and at 12 weeks but not at 6 weeks. The reason for non significant increase in shoot biomass at 6 weeks is not clearly known. In the soil of pH 5.0, root biomass was also significantly increased by MPR application except at 12 weeks. In all the three sampling dates, MPR application resulted in significantly higher shoot biomass in the soil of pH 5.9 than in the soil of pH 5.0. However, there was a much higher increase in shoot biomass due to MPR application in the soil of pH 5.0 than in the soil of pH 5.9. Relative to the control, MPR application in the soil of pH 5.0 increased shoot biomass by 94%, compared to 36% in the soil of pH 5.9.

Generally, shoot and root DM production of *T. vogelii* seedlings was depressed severely by strong soil acidity. Depression of shoot and root DM production in the soil of pH 5.0 was due to P deficiency and higher acidity related constraints like Mn. The Mn concentrations were 144.1 and 68.7 mg Mn kg^{-1} for soil of pH 5.0 and pH 5.9, respectively (Table 7). Extreme soil acidity has been reported elsewhere to depress biomass accumulation of *T. vogelii* and *C. cajan* (Drechsel *et al.*, 1996) and *T. candida* and *C. juncea* (Kadiata *et al.*, 1996).

The findings obtained in this study were similar to observations made on *L. leucocephala* and *G. sepium* seedlings (Mwendwa *et al.*, 1999), *S. sesban* (Ndung'u and Okalebo, 1999; Njeri and Okalebo, 1999) and on *M. pruriens* and *L. purpureus* (Vanlauwe *et al.*, 2000). In these studies, shoot dry weights of these species were significantly ($P \leq 0.05$) increased by PR application. However, contradictory results with *C. ochroleuca, M. pruriens, C. cajan* and *S. sesban* grown in a soil with pH 5.1 and Bray-II P of 7 mg kg^{-1} were reported by Balasubramanian and Sekayange (1992). Their study indicated that application of 9-40 kg P ha^{-1} had no effect on the biomass production of these species.

Application of MPR to both soils led to significant improvements in shoot and root DM production of *T. vogelii* seedlings. The significant increase in shoot and root DM production could be due to liming effect of MPR and improvement of P supply as the two soils were deficient in P (Table 7). High CaO content found in MPR (50.1%) (Table 9), make this material to have some liming effect. Phosphorus is essential in increasing growth rate of N_2-fixing plants. In Rwanda, Drechsel et al. (1996) reported that P deficiency limited biomass production of *T. vogelii*.

4.2.1.3 Number of nodules

The influence of soil pH and MPR application on the number of nodules per pot at 3, 6 and 12 weeks of growth of *T. vogelii* is shown in Table 12. The nodule numbers at soil pH 5.0 without MPR application were significantly lower than in the other treatments at all the three sampling periods. The increase in number of nodules in the soil of pH 5.9 relative to soil of pH 5.0 was 256%. Application of MPR to soil of pH 5.0 significantly improved the number of nodules only at 3 weeks of age but not in 6 or 12-week old plants. The numbers of nodules on plants at 6 and 12 weeks were slightly improved by MPR application from 11 to 12 nodules pot^{-1} (9% increase) and from 16 to 21 nodules pot^{-1} (31% increase), respectively. On the other hand, the numbers of nodules in the soil at pH 5.9 were significantly increased by MPR application throughout the 12-week period and were higher than those found in the soil of pH 5.0. This observation suggests that the soil of pH 5.0 had factors other than P and Ca that limited nodulation of *T. vogelii* seedlings.

Similar effects of pH on nodule numbers have been reported widely. For instance, Kadiata *et al.* (1996) reported that the number of nodules of woody and shrub legumes were significantly lower in an acid Ultisol than in a non-acid Alfisol. Aggarwal (1994) reported a linear increase in nodule numbers of 15 bean varieties as Al saturation was decreased to ≤ 25% by liming. On soils with pH ranging from 5.8 to 7.0 and available P from 0.2 to 6.6 mg P kg^{-1}, Giller *et al.* (1998) reported that addition of P fertilizer (26 kg P ha^{-1}) dramatically increased the number of root nodules of *Phaseolus vulgaris* in farmer's fields in the West Usambara Mountains in North-east Tanzania.

Table 12. Effect of soil pH and MPR application on number of nodules formed on *T. vogelii* roots

Treatment	Number of nodules per pot		
	3 WAE	6 WAE	12 WAE
Soil pH 5.0 without MPR	0.3 c	11.3 c	16.0 c
Soil pH 5.0 with MPR	12.0 b	12.0 c	21.0 c
Soil pH 5.9 without MPR	2.3 c	66.0 b	57.0 b
Soil pH 5.9 with MPR	35.0 a	122.0 a	94.0 a

Means with the same letter within a column are not statistically different by DMRT at $P \leq 0.05$

Extreme soil acidity depresses nodulation of N_2-fixing plants (Mengel and Kirkby, 1982). Nodule number of *T. vogelii* seedlings was significantly increased due to increasing soil pH (Table 12). According to Mengel and Kirkby (1982) extreme soil acidity decreases number of nodule formed because such soil condition leads to low microbial activity. Application of MPR further increased the number of nodules in both soils (Table 12). The increase in nodule number due to MPR application was due to necessity of P as nutrient in N_2-fixation processes in the nodule. Gibson *et al.* (1982) reported that nodules contain up to 3 times more P per unit DM than the roots

4.2.1.4 Quality of *T. vogelii* biomass

Table 13 gives the quality of shoot biomass in terms of shoot N and P concentrations and their uptakes as influenced by soil pH and MPR application in 12 week old *T. vogelii* seedlings. The N concentration in seedlings grown at pH 5.0 and at pH 5.9 without MPR application were statistically similar. Based on the N concentrations of *T. vogelii* biomass reported elsewhere, which range from 2.85 to 4% N (Gachene *et al.*, 2000; TSBF, 1999), the quality of biomass found in this study without MPR application is low. Application of MPR significantly improved the biomass quality, the increase being higher in the soil of pH 5.0 than in the soil of pH 5.9. In the soil of pH 5.0, MPR application increased N concentration of biomass from 2.3% to 3.5% while in the soil of pH 5 9 the corresponding increase was from 2.5% to 3.2%.

Table 13. Effect of soil pH and MPR application on shoot N and P concentration and uptake of 12 week old *T. vogelii*

Treatment	N		P	
	Concentration (%)	Uptake (g pot^{-1})	Concentration (%)	Uptake. (g pot^{-1})
Soil pH 5.0 without MPR	2.32 c	0.43 c	0.22 d	0.04 c
Soil pH 5.0 with MPR	3.53 a	1.26 a	0.32 b	0.12 ab
Soil pH 5.9 without MPR	2.53 c	0.95 b	0.25 c	0.09 bc
Soil pH 5.9 with MPR	3.21 b	1.28 a	0.35 a	0.18 a

Means with the same letter within a column are not statistically different by DMRT at $P \leq 0.05$

Thus, MPR application increased N concentration to levels comparable to those reported by Gachene *et al.* (2000) and TSBF (1999). The increase in N concentration of the biomass due to MPR application in the soil of pH 5.0 is equivalent to 52%, whereas in the soil of pH 5.9, the corresponding increase was only 28%. The quality of biomass in terms of N uptake was significantly improved by both the effect of soil pH and by MPR application. Relative to the soil of pH 5.0, the N uptake by *T. vogelii* seedlings in the soil of pH 5.9 was increased by 121%. Application of MPR in the soil of pH 5.0 significantly increased the N uptake by *T. vogelii* seedlings by 193%, whereas in the soil of pH 5.9, the corresponding increase was only 35%. Amending the two soils with MPR resulted in statistically similar shoot N uptake. These observations suggest that, MPR was effective in correcting most limitations associated with strong acidity and P-deficiency which reduced nodulation, N fixation and its uptake by *T. vogelii* seedlings.

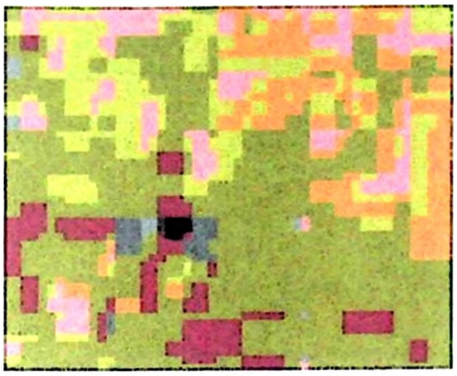
The P concentration and P uptake values of 12 week old *T. vogelii* seedlings as influenced by soil pH and MPR application are also presented in Table 13. The biomass P concentration was significantly improved by 14% due to the effect of soil pH from 5.0 to 5.9. Minjingu PR application significantly increased biomass P concentration by 46% in the soil of pH 5.0 and by 40% in the soil of pH 5.9. Biomass P content from the two soils without MPR application was increased by 125% due to increase in soil pH from 5.0 to 5.9, implying that P was more available at pH 5.9 than at pH 5.0. Biomass P contents were also significantly increased by MPR application on both soils, with more response in the soil of pH 5.0 than in that of pH 5.9. The percent increase in biomass P contents due to MPR application was 200% and 100% in the soil of pH 5.0 and pH 5.9, respectively. However, the P uptake values for the two soils when MPR was applied were non significantly different, suggesting that the effect of P on *T. vogelii* was more pronounced in the soil of pH 5.0 than in the soil of pH 5.9. This is probably due to higher MPR solubility in the soil of pH 5.0.

These results are similar to those reported by Mgangamundo (2000) for *T. vogelii* on acid soils (pH < 6.0) with low P (Bray-1 P < 3.3 kg ha^{-1}) without P application; and by Njeri and Okalebo (1999) for *S. sesban* on acid soils (pH < 5.8) with low P (< 4.4 mg P kg^{-1}) treated with MPR. In a field experiment at Gairo, Tanzania Mgangamundo (2000) observed that one-year old *T. vogelii* biomass contained 2.6% N. Njeri and Okalebo (1999) found that MPR application significantly increased the number of effective nodules in *S. sesban* and N and P uptake. Similarly, Vanlauwe *et al.* (2000) observed that addition of PR enhanced N and P contents of *M. pruriens* and *L. purpureus*. In contrast, Balasubramanian and Sekayange (1992), reported that P application at rates ranging from 9 to 40 kg P ha^{-1} in a soil with pH 5.1 and 7 mg kg^{-1} Bray-II P had no effect on biomass yield and N content of *C. ochroleuca, M. pruriens, C. cajan* and *S. sesban*. It is therefore evident that PR application improves the quality of fallow plants by increasing N and P contents where native soil P levels are very low (< 6.0 mg P kg^{-1}).

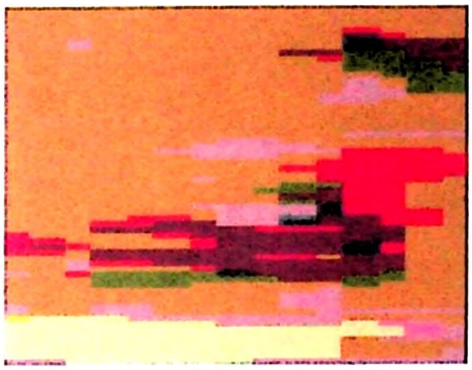
4.2.1.5 Relative capacity for active N_2-fixation in *T. vogelii* seedlings

Relative capacity for active N_2-fixation in *T. vogelii* seedlings at 12-week was assessed by examining effectiveness of nodule tissues. The nodule tissue of actively N_2 fixing nodule (effective nodule) is distinctly red or pink in colour because of the presence of an iron-containing substance called leghaemoglobin, whereas nodule tissue of ineffective rhizobia has white or green pigmentations (Alexander 1985). As effective nodules age, the cells loose leghaemoglobin and their nodular tissue become brown in colour (Wild, 1988). Plates 1a, 1b, 1c, and 1d depict the colours of enlarged 12-week old *T. vogelii* nodular tissue in soil of pH 5.0 without MPR, pH 5.0 with MPR, pH 5.9 without MPR, and pH 5.9 with MPR, respectively.

The nodular tissue in soil of pH 5.0 without MPR application was dominated by green pigmentation, and in a few patches there were red, pink or brown colourations (plate 1a). The coverage of red, pink or brown pigmentations was increased and green colouration was reduced in the nodular tissue of soil of pH 5.0 that was amended with MPR (Plate 1b), indicating that relative capacity for active N_2-fixation of *T. vogelii* seedlings was improved by MPR application. In soil of pH 5.9 without MPR application, the nodular tissue was dominated by red, pink or brown pigmentations, with few patches of green colouration (Plate 1c). The nodular tissue in soil of pH 5.9 with MPR application was dominated by red, pink or brown pigmentations (Plate 1d). The relative low coverage of red, pink or brown pigmentations and hence low N_2-fixation in soil of pH 5.0 as evidenced by significantly lower shoot N concentration and uptake (Table 13), was due



(a)



(b)

(c)

(d)

Plate 1. Colour of nodule tissue of 12-weeks old *T. vogelii* seedlings in (a) soil pH 5.0 without MPR, (b) soil pH 5.0 with MPR, (c) soil pH 5.9 without MPR, and (d) soil pH 5.9 with MPR

Legend:

Green nodular tissue-non N_2-fixing parts of a *T. vogelii* nodule

Pink nodular tissue-higher N_2-fixing parts of *T. vogelii* nodule

Red nodular tissue-higher N_2-fixing parts of *T. vogelii* nodule

Brown-degenerating effective N_2-fixing parts of *T. vogelii* nodule

Orange nodular tissue-lower N_2-fixing parts of *T. vogelii* nodule

Pinkish red nodular tissue-higher N_2-fixing parts of *T. vogelii* nodule

Pink nodular tissue-higher N_2-fixing parts of *T. vogelii* nodule.

to P deficiency and more severe acidity related constraints like high Mn levels in this soil than in the soil of pH 5.9 (Table 7). Drechsel *et al* (1996) reported that extreme acidity and deficiencies of P and micronutrients severely depressed N_2-fixation of N_2-fixing legumes. Alexander (1985) reported that about 1 mg of P is assimilated by N_2-fixing bacteria for each 5 to 10 mg of N_2-fixed in the nodules, and that in strongly acidic soils, there are very few organisms that could neither grow nor fix N2 in the nodule.

Increase in the amount of leghaemoglobin (intense coverage of red or pink pigmentations) increase N_2- fixation. Alexander (1985) reported that the amount of N_2-fixation per plant was increased with increase in leghaemoglobin content and hence degree of effectiveness in the nodular tissue of pea plants.

The nodular tissue pigmentation observed in this experiment suggests that the relative capacity for active N_2-fixation in soil of pH 5.0 was low and was increased only to a small extent by MPR application. This is because MPR applications cannot eliminate all the problems associated with extreme acidity including high Mn levels observed. The relative capacity for N_2-fixation of *T. vogelii* seedlings in soil of pH 5.9 was improved at high pH but was best when it was amended with MPR. These observations imply that soil conditions especially deficient P levels in soil of pH 5.9 (Table 7), still limited N_2-fixation of *T. vogelii* plants, and were further improved by MPR application (Table 13).

It is evident from the above results that *T. vogelii* plants are very sensitive to strong soil acidity (pH < 5.5) and to low Bray-I P (< 10 mg P kg^{-1}), by depressing plant height, biomass quantity and quality, number of root nodules, and effectiveness of root nodules. In moderate soil acidity (pH > 5.5) and low Bray-I P, the performance of *T. vogelii* seedlings was favourable in most of these parameters. Application of MPR to both soils further improved the performance of *T. vogelii* with higher response in the lower pH soil. This study further revealed that MPR application alone in low pH soil did not eliminate all soil factors limiting nodulation and hence N_2-fixation of *T. vogelii* plants.

4.2.2 *Tephrosia vogelii* response to P and Ca applications on a strongly acid P deficient Ferralsol

The objective of this study was to establish which of the two elements namely P and Ca supplied by MPR was most limiting to *T. vogelii* growth on a P deficient acid (pH 5.0) Ferralsol. The data collected were shoot DM yields and shoot N, P and Ca concentrations.

4.2.2.1 Shoot DM yield

The effects of P and Ca applications on a strongly acid P deficient Ferralsol on shoot DM yield of 12-week old *T. vogelii* seedlings are given in Table 14. Shoot DM yields were significantly increased by Ca and P applications as MPR by 26%, but application of either Ca or P alone had no effect. Combined application of Ca as $CaSO_4$ and P as KH_2PO_4 at higher rates had slightly less effect (18.2%) on DM yields than that of MPR.

Much smaller effects on DM yields ranging from 13-14.6% were observed at lower rates of Ca and P applications. Sources of Ca and P appear to affect DM yields of *T. vogelii* seedlings. Application of Ca and P as $CaSO_4$ + KH_2PO_4 and as MPR increased DM yields by 18.2 and 26%, respectively, implying that other elements in the MPR are confounding the results. However, the increase in DM yields due to MPR application at 160 mg P kg^{-1} is lower (26%) than that of 94% obtained from 400 mg P kg^{-1} (Table 11), suggesting that for optimum DM production of *T. vogelii* seedlings in strongly acid P deficient Ferralsols, higher P levels are required.

4.2.2.2 Shoot Ca, P and N concentrations

Shoot Ca, P and N concentrations in 12-week old *T. vogelii* seedlings are given in Table 14. Shoot P and N concentrations were significantly increased by Ca and P applications, but not shoot Ca concentrations. Based on the adequate range for nutrition of bean (*Phaseolus vulgaris*) of 0.8-3.0% Ca in fully mature leaf blades (Reuter and Robinson, 1986), shoot Ca concentrations of 0.83-0.90% observed in this experiment may be within the adequate range for nutrition of 12-week old *T. vogelii* seedlings.

Soils that were not amended with P had significantly lower and deficient shoot P concentrations (< 0.24% P), while P amended soils had significantly higher and adequate shoot P concentrations (> 0.24%). The effects of sources or rates of Ca and P on shoot P concentration were similar. Good responses to P applications on acid soils have also been reported for other leguminous trees or shrubs including *Sesbania goetzei*, *L. leucocephala*, *G. sepium*, *S. sesban* and *C. calothyrsus* (Luyindula and Haque. 1992; Ndufa *et al.*, 1999; Sanginga *et al.*, 1994).

Application of P, but not Ca alone, led to significant increase in shoot N concentrations. Rates of P had a significant effects, while Ca rates had no effect on shoot N concentrations. However, shoot N concentrations observed are lower than levels reported here in a previous glasshouse study using the same species and soil, but at higher P rate (Table 13), implying that the P levels applied in this experiment were not sufficient for adequate N_2-fixation.

Table 14. Influence of P and Ca applications on DM yield and shoot Ca, P and N concentrations of 12-week old *T. vogelii* plants

Ca and P treatments		Shoot DM	Shoot N, P and Ca concentrations (%)		
(mg Ca kg^{-1})	(mg P kg^{-1})	yield (g pot^{-1})	Ca	P	N
0	0	19.2 b	0.83 a	0.13 b	2.18 d
436[1]	0	20.3 b	0.84 a	0.16 b	2.20 d
436[1]	80[3]	21.7 ab	0.85 a	0.36 a	2.40 cd
0	160[3]	19.9 b	0.85 a	0.34 a	2.52 bc
218[1]	160[3]	22.0 ab	0.80 a	0.39 a	2.78 a
436[1]	160[3]	22.7 ab	0.90 a	0.36 a	2.69 ab
436[2]	160[4]	24.2 a	0.85 a	0.34 a	2.82 a

Means bearing the same letter within a column are similar by DMRT at $P \leq 0.05$
[1]Ca source was $CaSO_4$
[2]Ca source was MPR
[3]P source was KH_2PO_4
[4]P source was MPR

4.2.2.3 Relationship between DM yield and shoot N, P and Ca concentrations

Simple correlation analysis was used to establish the association between DM yields and shoot N, P and Ca concentrations. Table 15 gives correlations between DM yields and shoot

Ca, P and N concentrations, and between shoot N concentrations and shoot Ca and P concentrations. Dry matter yields were significantly correlated with concentrations of P (r = 0.99) and N (r = 0.83) in shoots, but not with shoot Ca concentrations.

Table 15. Correlations between DM yields and shoot Ca, P and N concentrations, and between shoot N concentrations and shoot Ca and P concentrations

Parameters correlated	Correlation coefficient (r) (df = 5)	Significance
DM yield vs shoot Ca conc	0.23	ns
DM yield vs shoot P conc.	0.99	**
DM yield vs shoot N conc	0.83	*
Shoot N conc. vs shoot Ca conc.	0.11	ns
Shoot N conc. vs shoot P conc.	0.84	*

* Significant at 5% level
** Significant at 1% level
ns Non significant

Shoot N concentrations were significantly correlated with shoot P concentrations (r = 0.84), but not with shoot Ca concentration. The response data of *T. vogelii* to P and Ca application (Tables 14) and simple correlation analysis (Table 15) reveal that P and N were more limiting to *T. vogelii* growth than Ca on strongly acid P deficient Ferralsols. The data also indicate that the most important contribution of MPR was in improving P rather than Ca supply.

4.2.3 Effects of MPR application to a Ferralsol on *T. vogelii* performance

This experiment evaluated the effect of MPR application and prevailing weather on the performance of *T. vogelii* under field conditions in an acidic P deficient Ferralsol in terms of agronomic parameters and quantity and quality of biomass produced. The parameters assessed were survival, number of diseased plants, plant height, root collar diameter, litter N and P concentrations, total N and P accumulations in the litter, foliar N and P concentrations, total N and P accumulations in the leaves, and total litter, leaves and stem DM production.

4.2.3.1 Survival of *T. vogelii*

The survival of *T. vogelii* plants as affected by MPR application and seasons is given in Table 16. At each specific fallow age, MPR amendment had no effect on the survival of *T. vogelii* plants. However, the overall mean survival was significantly reduced from 51.0% in the control to 43.3% in the MPR applied plots (Table 17). In both P treatments, the survival of *T. vogelii* decreased with fallow age starting from 97% at one-month to about 21% at 22-months after establishment.

The decreased survival with age closely followed the trend of rainfall distribution. The survival of *T. vogelii* plants was significantly affected by the long dry season (Table 17), affecting young plants more than older plants. Despite watering *T. vogelii* plants at the rate of one litre plant^{-1} twice a week from mid August to late November in the year 2000, the survival of young *T. vogelii* plants was significantly reduced from 97% at the end of the long rains to about 50% six months later at the onset of the short rains. A similar pattern of decrease in survival of *T. vogelii* plants was also observed in the long dry season at the age of 13 to 18-months, though the severity was lower than that of the previous year. A long dry season appears to be one of the most limiting factors affecting establishment and growth of young *T. vogelii* plants. Kwesiga *et al.* (1999) also reported that during the establishment and growth of improved fallows of *T. vogelii* in farmer's fields in Zambia, low and sporadic rainfall reduced survival from 91% at six months to 51% one year after planting. In a high rainfall year, the survival rate at one year after planting exceeded 60% (Kwesiga *et al.*, 1999)

Table 16. Effect of MPR application and seasons on survival, disease infection, plant height and root collar diameter of *T. vogelii* plants over 22-month

Fallow age (months)	Season	P rate (kg P ha^{-1})	Survival	Diseased plants	Plant height	Root collar diameter
			-----(%)----		-----(cm)----	
0-1	Wet	0	97.4 a	2.2 a	nm	nm
	Wet	80	97.2 a	2.5 a	nm	nm
2-6	Dry	0	53.6 a	1.5 a	58.3 b	1.0 a
	Dry	80	51.6 a	1.5 a	82.8 a	1.3 a
10-12	Wet	0	43.0 a	2.5 a	103.7 b	1.7 b
	Wet	80	43.6 a	3.8 a	129.5 a	2.4 a
13-18	Dry	0	38.6 a	2.0 b	168.2 b	2.7 b
	Dry	80	34.2 a	4.8 a	199.8 a	3.5 a
19-22	Wet	0	22.7 a	1.2 a	178.6 b	2.9 b
	Wet	80	20.2 a	1.8 a	215.1 a	3.7 a

Means bearing the same letter within a column at the same fallow age are similar using t-test at $P \leq 0.05$
nm: not measured

4.2.3.2 Disease and pests infection in *T. vogelii* fallow

The major disease and pest problems encountered were Fusarium wilt and root-knot nematodes. The cause of Fusarium wilt infection is reported to be ***Fusarium spp*** or ***Verticellium spp.*** (Agrios, 1997). The wilt was more severe when low temperature, drought or excessive moisture stresses prevailed. The symptoms of Fusarium wilt observed were a whitish ring on the root collar region, loss of turgidity in the lower leaves, greenish yellow leaves and wilting. Table 17 gives the extent of Fusarium wilt infection on *T. vogelii* plants over a 22 months growth. Fusarium wilt significantly affected MPR amended plots in the wet season than dry season, although significantly higher incidences were also observed in the dry season of the year 2001 that was perhaps due to a spill over effect of inoculum from the previous wet season. Over the 22-month period, the survival of *T. vogelii* plants was reduced by 11.8% due to Fusarium wilt infestation (Table 17).

Table 17 Seasonal effects on survival, disease infection, plant height and root collar diameter of *T. vogelii* plant over 22-month

T. vogelii fallow age (months)	Season	Survival	Diseased plants	Plant height	Root collar diameter
		-----(%)----		-------(cm)-----	
1 (0-1)	End (Wet)	97.3 a	2.3 ab	nm	nm
6 (2-6)	End (Dry)	52.6 b	1.5 b	70.5 d	1.2 c
12 (10-12)	End (Wet)	43.3 c	3.1 a	116.6 c	2.1 b
18 (13-18)	End (Dry)	36.4 c	3.4 a	184.0 b	3.1 a
22 (19-22)	End (Wet)	21.4 d	1.5 b	196.8 a	3.3 a

Means bearing the same letter within a column are similar by DMRT at $P \leq 0.05$
nm: not measured

At uprooting the fallows, root-knot nematodes (*Meloidogyne spp*) were observed on roots of *T. vogelii*. However, in this study the extent of nematode infection was not assessed. Root-knot nematode infection on the roots of *T. vogelii* plants has also been observed in Western Kenya (Kamiri *et al.*, 2001; Amadalo *et al.*, 2003). Nematodes interfere with nodulation of many legumes and decrease the specific N_2-fixation activity of the nodules (Gibson *et al.*, 1982).

4.2.3.3 Plant height

The influence of MPR application on height of *T. vogelii* plants is given in Table 16. Application of MPR significantly increased plant height throughout the experimental period. Seasons (dry *vs* wet seasons) also significantly affected plant height, with greater increase in height during rainy season and shortly after the rains and less increase in the dry season (Table 17). Greater height of *T. vogelii* seedlings on acid P deficient Ferralsol that was amended with MPR was also observed in a 12-week glasshouse study (Table 10).

Other N_2-fixing species such as *A. auriculiformis*, *M. pruriens*, *A. lebbeck*, *G. sepium*, *L. diversifolia*, *L. leucocephala* cv. K28 and K636, *L. sericeus*, *C. cajan*, *T. candida*, *S. sesban* and *C. calothyrsus* have shown similar effect on acid soil and to P application on P deficient soils (Kadiata *et al.*, 1996; Lyasse *et al.*, 2002; Ndufa *et al.*, 1999; Sanginga *et al.*, 1994). However, contradictory results with *C. ochroleuca, M. pruriens, C. cajan* and *S. sesban* grown in a soil of pH 5.1 and Bray-II P of 7 mg kg^{-1} were reported by Balasubramanian and Sekayange (1992). Their study indicated that application of 9-40 kg P ha^{-1} had no effect on the biomass production of these species. This observation suggests that Bray-II P of 7 mg kg^{-1} is adequate for nutrition of *C. ochroleuca, M. pruriens, C. cajan* and *S. sesban*.

Basically, plant height of N_2-fixing plants is limited by soil acidity and P deficiency (Mengel and Kirkby 1982). In the 22-month period, soil acidity (pH 5.06) and P deficiency (2.1 mg P kg^{-1}) (Table 6) significantly reduced plant height of *T. vogelii* plants. Application of MPR led to significant increase of plant height, indicating that MPR corrected both acidity and P deficiency

4.2.3.4 Root collar diameter

Table 16 gives root collar diameter of *T. vogelii* plants as affected by MPR application over seasons. At < 12 months, root collar diameter was not affected by MPR application. However, root collar diameter was significantly increased by MPR application in plants of age $\geq$ 12 months. The percent increase in root collar diameter due to MPR application for 12, 18 and 22-month old plants was 41, 30 and 31, respectively. This observation suggests that stems of *T. vogelii* plants accumulate more DM at more than 12 months age, and that MPR application further increased the magnitude of DM accumulation in stems. Increased stem DM accumulation of *T. vogelii* plants at more than 12 months age was also observed in Western Kenya by George *et al.* (2002b).

4.2.3.5 Litterfall production

Table 18 presents the amount of litterfall produced by *T. vogelii* fallows of between 12 and 22 months in relation to MPR application. The amount of litterfall in all the collection periods was significantly increased by MPR application, with much more litter collection during the dry seasons than in the wet seasons (Fig. 4). The total litter produced during dry months (month 14-18) was significantly higher by 62% than in the wet months (Appendix 5), confirming that dry season hastens leaf senescence of *T. vogelii* plants.

Litter production has followed a trend observed on other growth parameters like plant height and nodule number on responding to soil acidity and P deficiency. In the 22-month period, litter production was significantly reduced by soil acidity and P deficiency (Table 18). Application of MPR at fallow establishment significantly improved the litter production at each sampling period. This observation further support previous observation that MPR is both a P source and a liming material.

4.2.3.6 N and P concentrations in litter

The litter N and P concentrations during the 12-22 month period as influenced by MPR application are presented in Table 18. In the five litter collections, N concentrations were not affected by both soil acidity and MPR application, while litter P concentrations were significantly increased by MPR application only in some collections.

Litter P but not litter N concentrations were significantly affected by season (Fig. 5). In most cases during dry season, litter P concentration was significantly higher in plots treated with MPR. During the dry season, soil acidity and P deficiency depressed litter P concentrations, and possibly reduced the movement of P from senescent to young leaves.

Table 18 Effects of MPR application on amount of *T. vogelii* litterfall, N and P concentrations and accumulations over 12 to 22 month period

Fallow age (months) / season	P rate (kg P ha^{-1})	Litter DM (t ha^{-1})	Litter N and P concentrations -----(%)-----		Total litter N and P accumulations -----(kg ha^{-1})-----	
			N	P	N	P
10-12 / wet	0	0.517 b	1.40 a	0.05 b	7.24 a	0.25 b
	80	1.203 a	1.45 a	0.08 a	17.44 a	0.84 a
13-14 / dry	0	0.289 b	1.43 a	0.05 a	4.13 a	0.13 b
	80	0.788 a	1.45 a	0.05 a	11.43 a	0.42 a
15-16 / dry	0	0.688 b	1.45 a	0.05 b	10.18 b	0.33 b
	80	1.585 a	1.45 a	0.08 a	24.03 a	1.18 a
17-18 / dry	0	0.481 b	1.35 a	0.05 b	6.95 b	0.24 b
	80	1.354 a	1.45 a	0.07 a	20.42 a	0.95 a
19-22 / wet	0	0.459 b	1.20 a	0.04 a	5.56 a	0.21 a
	80	0.762 a	1.20 a	0.04 a	9.25 a	0.30 a

Means bearing the same letter within a column and fallow age are similar using t-test at $P \leq 0.05$

The N and P concentrations in the litter are low, thus resulting in low quality litter. The low N and P concentrations in the litter were due to re-absorption of these nutrients from senescent to young leaves (Mengel and Kirkby, 1982). Since the mean OC content of *T. vogelii* litter was 48.95%, application of *T. vogelii* litter may lead to P immobilization, due to a very wide C:P ratio of 890. According to Singh and Jones (1976), C:P ratio > 130 lead to P immobilization in organic material.

4.2.3.7 Periodic N and P accumulations in litter

Periodic litter N and P accumulations as influenced by MPR application are given in Table 18. Application of MPR significantly increased periodic litter N accumulation at 16 and 18 months and P accumulation up to 18 months. The influence of MPR

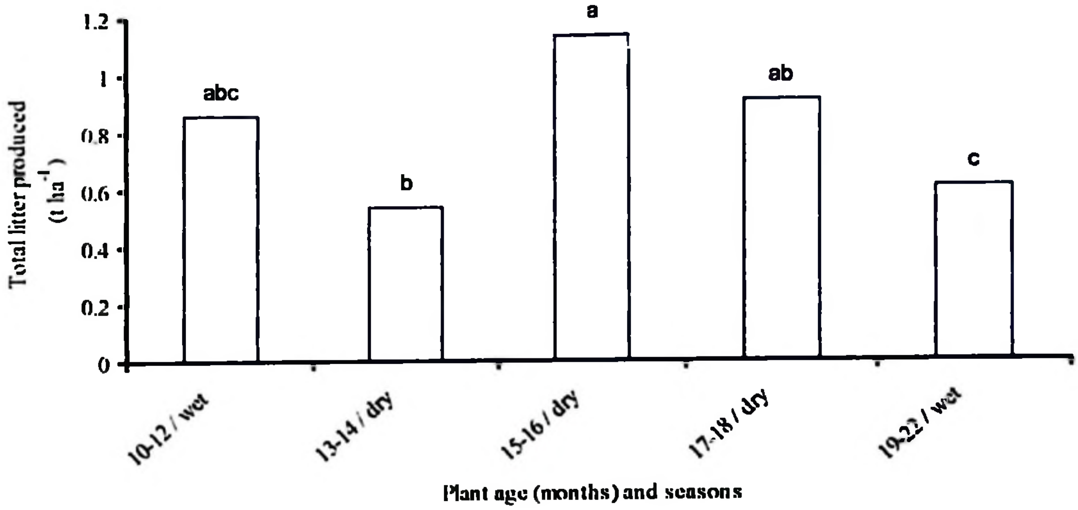


Figure 4. Influence of seasons on the amount of litter production

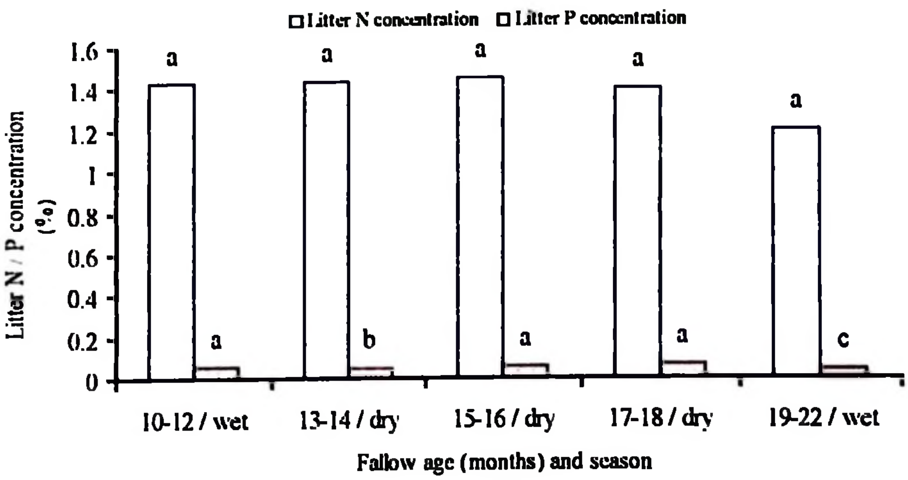


Figure 5. Effect of seasons on litter N and P concentrations

application was significantly greater for periodic P accumulation in the litter than N accumulation Total litter N accumulation was significantly higher in the dry than in wet season. Seasonal variation had no influence on total litter P accumulation (Fig. 6).

Periodic N and P accumulation in the litter followed the trend of litter accumulation. In case of N accumulation, soil acidity and P deficiency significantly depressed it at 15-18 month period, while litter P accumulation was significantly depressed almost throughout the 22-month period. Significant depression of N and P accumulated in the litter was due to significant increase of litter production caused by MPR application.

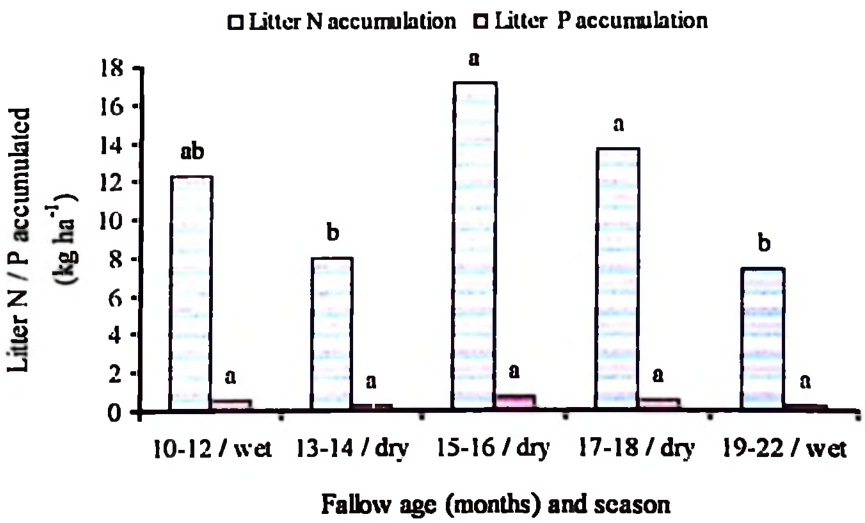


Figure 6. Effect of seasons on litter N and P accumulations

4.2.3.8 Leaf N and P concentrations

The leaf N and P concentrations as influenced by MPR application at various ages are given in Table 19. Throughout the 22-month period, the leaf N concentrations were not affected by MPR application, suggesting that N uptake from the two MPR treatments were similar. Non significant increase in N concentrations were also observed on *M. pruriens*, *Desmodium distortum*, and *C. cajan* which had been treated with P fertilizer at rates ranging from 9-40 kg P ha^{-1} (Balasubramanian and Sekayange, 1992).

Table 19. Effect of MPR application on leaf N and P concentrations of 6-, 12-, 18- and 22-month old *T. vogelii* plants

Fallow age (months)	P rate (kg P ha^{-1})	Leaf N and P concentration (%)		C:N and C:P ratios	
		N	P	C:N	C:P
6	0	2.7 a	0.05 b	16.3	878.0
	80	2.9 a	0.17 a	15.1	258.2
12	0	2.8 a	0.10 b	15.7	439.0
	80	3.0 a	0.13 a	14.6	337.7
18	0	2.4 a	0.10 a	18.3	439.0
	80	2.5 a	0.10 a	17.6	439.0
22	0	3.2 a	0.13 a	13.7	337.7
	80	3.3 a	0.13a	13.3	337.7

Means bearing the same letter within a column and fallow age are similar using t-test at $P \leq 0.05$

Despite application of MPR at *T. vogelii* fallow establishment, the foliar N concentration was relatively low compared to foliar N concentration of 4% reported in Madagascar by Murwira *et al.* (2002). High Mn levels and low soil pH are likely to have depressed rhizobia activity and hence biological N_2-fixation. The critical level below which Mn responses is expected in soils is < 25 mg kg^{-1} soil (Wild, 1988), while the content in the soil used in this study was 226 mg kg^{-1} (Table 6) High levels of Mn can be toxic to plants. Toxicity occurs when the Mn concentrations is in excess of plant requirement, for instance 160 mg Mn kg^{-1} in mature leaves of soyabean (Mengel and Kirky, 1982). However, Jones and Farrar (1999) reported that root exudates relieve metal toxicities. Table 19 further indicate variations of C:N ratios of *T. vogelii* leaf samples collected over the 22-month period. Throughout the 22-months, the leaves of *T. vogelii* had C:N ratios of < 30, which according to Giller and Wilson (1991) is within the C:N ratios of other legume residues. The lower C:N ratios observed (Table 19) suggests that the leaves of *T. vogelii* are likely to decompose more rapidly with net mineralization of N occurring right from the beginning.

Unlike foliar N concentrations, leaf P concentrations were significantly increased by MPR application at the age of 6 and 12-month. Non significant difference in leaf P concentrations at 18 and 22 months was probably caused by increased P uptake from organic P (Po) mineralized by plant roots (George *et al.*, 2002a). In a rhizopot study using a P deficient Ferralsol, George *et al.* (2002a) observed that *T. vogelii* roots enhanced mineralization and solubility of Po through rhizosphere phosphatase activity. Phosphorus deficiency enhances the release of phosphatase enzyme, but release is depressed by addition of inorganic P fertilizers (Jones and Farrar, 1999). However, the leaf P concentration was much lower than the critical concentration of 0.24% for net P mineralization (Palm *et al.*, 1999). Similarly, the C:P ratio was wider than the critical C:P ratio of 130 above which P immobilization of organic material is expected (Singh and Jones, 1976). The two unfavourable indices suggest that application of *T. vogelii* leaves may lead to P immobilization at least in the short term.

On average, leaf N and P concentrations increased with age but were significantly reduced at 18 months, which was in the dry season. Prolonged drought reduces P uptake, inhibits nodulation and rhizobium activity, which consequently reduces N_2-fixation (Abebe, 1994; Hernandez-Ameta *et al.*, 1989)

Both leaf N and P concentrations varied with season. In most cases, the concentrations of these nutrients fluctuated with higher values in wet and lower values in dry seasons (Fig. 7). This is contrary to the observations made at Gairo which showed a decreasing trend of leaf N and P concentrations with plant age on P unfertilized *T. vogelii* fallows (Mgangamundo, 2000). The leaf N and P concentrations as expected, were considerably higher than litter N and P concentrations (Tables 18, 19). This is due to re-absorption of N and P from the senescent to young leaves (Mengel and Kirkby, 1982).

4.2.3.9 Total litter, leaves and stem production

The total amounts of litter, leaves and stem DM production in the 22 months period are given in Table 20. Application of MPR significantly increased litter and stem DM but not leaf DM. Non significant increase in foliar DM production indicates that seasonal effects confounded the effect of MPR. In Western Kenya, George *et al.* (2002b) observed that leaf biomass of 12-month old *T. vogelii* plants declined while stem DM increased. At

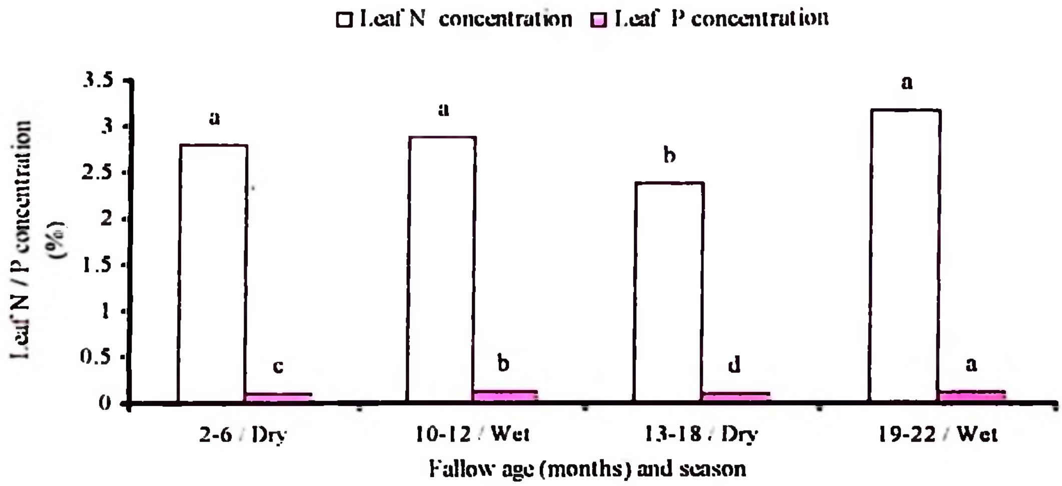


Figure 7. Influence of fallow age and seasons variation on leaf N and P concentrations

Table 20. Effect of MPR application on total litter, leaf and stem production of 22-month old *T. vogelii* fallows

Plant component	P rate (kg P ha^{-1}	Total DM (t ha^{-1})	Increase due to P application (%)
Litterfall	0	2.49 b	-
	80	5.69 a	129
Leaves	0	0.39 a	-
	80	0.45 a	14
Stems[1]	0	4.09 b	-
	80	6.78 a	66

Means bearing the same letter within a column and same plant component are similar using t-test at $P \leq 0.05$

Stems[1]: Stems included some roots

the end of the 22-month period, the DM ratio of leaves:stems:litter was 5:59:36 in the control relative to 4:51:45 in the MPR treated soils. The observation in the current study suggests that application of MPR led to vigorous growth, which led to higher litter accumulation The total DM production was increased from 6.9 t ha^{-1} in the control to 12.9 t ha^{-1} in plots amended with MPR. This result showed that undercomparable climate and management conditions, amending P deficient Ferralsols with MPR would increase total DM production of *T. vogelii* plants by 86.9%.

Relative to other sites, the amounts of DM obtained for each plant component in this experiment are low. This could be attributed to the long dry season (6-months) and *Fusarium* wilt infection which led to decrease in survival from 97% at one-month to 20% at 22-month (Tables 16, 17). The amounts of litter and foliage obtained from 12-month *T. vogelii* fallows in Rwanda which experiences a dry season lasting 3 to 4 months were 4.8 and 2.6 to 2.7 t ha^{-1}, respectively (total 7.4 t ha^{-1}) (Balasubramanian and Sekayange, 1992, Hagedorn *et al.*, 1997). Rutunga *et al.* (1999) reported that in Western Kenya with a dry season of 3 months, a 6-month old *T. vogelii* fallow accumulated 9.5 t ha^{-1} of above and belowground biomass.

4.2.3.10 Average N and P concentrations in litter, leaves and stems

Table 21 presents the mean N and P concentrations in the litter, leaves and stems. Mean N concentrations were significantly increased by MPR application only in stems, while mean P concentrations in the three plant components were significantly increased by MPR application, reflecting increased P availability from applied the MPR.

Table 21 Influence of MPR application on concentration and total accumulation of N and P in litter, leaves and stems of *T. vogelii* fallows

Plant component	P rate (kg P ha^{-1})	Mean N and P concentration (%)		Total N and P accumulation (kg ha^{-1})	
		N	P	N	P
Litter	0	1.37 a	0.05 a	34.5 b	1.2 b
	80	1.40 a	0.06 a	82.5 a	3.7 a
Leaves	0	2.8 a	0.10 b	12.6 a	0.5 a
	80	2.9 a	0.13 a	14.6 a	0.6 a
Stems	0	0.46 b	0.04 b	18.6 b	1.8 b
	80	0.55 a	0.11 a	36.5 a	7.1 a

Means bearing the same letter within a column and plant component are similar using t-test at $P \leq 0.05$.

4.2.3.11 Total N and P accumulated in litter, leaves and stems

The total N and P accumulated in the litter, leaves and stems as influenced by MPR application is given in Table 21. The total N and P accumulated in the litter and stems were significantly increased by MPR application but total N and P in the leaves were not significantly affected. Non significant total N and P accumulations in the leaves were due to similar accumulation of foliar DM and foliar concentrations in N and P (Tables 20). Among the three plant components, litter provided more N than the other two components, accounting for 62% of the total N accumulated.

In the 22-month period, the total N accumulated in the three plant components were 65.7 and 133.5 kg ha^{-1} for control and MPR treated plots, respectively. The corresponding values for P were 3.4 and 11.3 kg ha^{-1}. The increase in total N and P accumulation in the three plant components due to MPR application was 103.2% for N and 232.6% for P.

The total N and P accumulated at this site due to MPR application were comparable to other sites evaluating *T. vogelii* plants Total N accumulations in *T. vogelii* fallows (which most of them where treated with P fertilizers) in Rwanda and Kenya ranged from 112-238 kg N ha^{-1} (Balasubramanian and Sekayange, 1992; Hagedorn *et al.*, 1997; Kamiri *et al.*, 2001; Rutunga *et al.*, 1999), whereas P ranged from 6 to 14 kg P ha^{-1} (Hagedorn *et al.*, 1997; Mganganmundo, 2000; Rutunga *et al.*, 1999). Amending a P deficient Ferralsol with MPR at this site increased total N and P accumulation of *T. vogelii* plant components and is likely to improve N and P status of the soil.

However, in control plots, relative to other sites evaluating the performance of *T. vogelii* fallows, the total N and P accumulated at this site is low. Low total N and P accumulated in control plots at this site was mainly due to low soil pH and inadequate P levels. Drechsel *et al.* (1996) also reported that acid P deficient Ferralsols depressed N and biomass accumulation of *T. vogelii* plants in Rwanda.

Tephrosia vogelii stems also contained substantial amounts of N and P. For instance in soils treated with MPR, *T. vogelii* stems contained 25 and 66% of the total N and P accumulated (Table 21), respectively. Large quantities of N and P were also accumulated in the stems of *S. sesban*, *C. calothyrsus* and *G. robusta* (Maroko *et al.*, 1999; Ndufa *et al.*, 1999). At 325 days after establishment, Ndufa *et al.* (1999) observed that *S. sesban*, *C. calothyrsus* Meissner and *G. robusta* accumulated 107-336 kg N ha^{-1}, 5.7-22 kg P ha^{-1} and 37-134 kg K ha^{-1}in woody products. Maroko *et al.* (1999) reported that 17 months old *S. sesban* stakes accumulated 9.0 kg P ha^{-1}. Since stems are frequently utilized as stakes and fuel wood, nutrients contained therein do not normally benefit the crop.

The benefits of tree fallows to soil fertility replenishment depend on the plant species (Barios *et al.*, 1997, Drechsel *et al.*, 1991), quantity and quality of biomass produced (Balasubramanian and Sekayange, 1992) and the length of fallow (Adejuwon and Adesina, 1990). In addition to these factors, this experiment has demonstrated that the benefits of fallow species on soil fertility also depend on survival of the species during the fallow phase.

In the acid P deficient Ferralsol of SUA Farm, *T. vogelii* fallow productivity appears to be adversely affected by prevailing weather conditions, soil acidity and P deficiency. Prevailing weather, especially the dry season of 5-6 month, reduced survival of *T. vogelii* plants by up to 64% during the 22-month period. Relative to plots treated with MPR, soil acidity and P deficiency limited fallow productivity it generated only 6.9 t ha^{-1} of biomass containing 65.7 kg N ha^{-1} and 3.4 kg P ha^{-1}. Application of MPR improved total biomass production, and total N and P accumulation by 1.5-, 2.0- and 3.3-fold, respectively. The improvement in *T. vogelii* fallow productivity due to MPR application is likely to improve N and P supplies and crop yields in the subsequent cropping season.

4.2.4 Performance of *T. vogelii* relayed with maize

This experiment assessed the performance of *T. vogelii* plants relayed with maize in the first post-fallow crop. The data collected from relayed *T. vogelii* plants included survival, plant height, foliar and stem biomass, and N and P concentrations and accumulations in the leaves.

4.2.4.1 Survival of *T. vogelii*

The survival of relayed *T. vogelii* plants both at 7 and 11-month of age as influenced by sources and combinations of nutrients is given in Table 22. At the age of 7 months, the survival of relayed *T. vogelii* plants treated with various sources and combinations of nutrients was higher than that in the control. The plots treated with MPR+SA had the highest survival of 89% while the lowest survival of 80% was in the plot treated with *T. vogelii* biomass+MPR. At the age of 11 months, the trend of survival of relayed *T. vogelii* plants was similar to that at 7 months, but the survival level was lower. The survival of relayed *T. vogelii* plants both at 7 and 11 months old was not affected by different fertilizer applications (Table 22). Compared to the first experiment established at the same site in the 1999/00 season, the survival of relayed *T. vogelii* was higher at both 7 and 11 months than at 6 and 12 months for the first fallow (Table 16). The mean survival of 7 and 11-month old plants was 81.4 and 69.4%, respectively compared to 52.6% at 6-month and 43.3% at 12 months in the first experiment.

Table 22. Influence of fertilizer application on relayed *T. vogelii* survival, plant height and biomass accumulation

Treatments	Survival (%)		Plant height (cm)		Biomass (t ha^{-1})	
	7-mo	11-mo	7-mo	11-mo	Leaves	Stem
Control	72.6 a	69.2 a	33.2 bc	73.8 a	0.095 b	1.25 b
MPR[2]+SA	89.2 a	70.6 a	41.9 abc	86.7 a	0.213 a	3.31 a
T. vogelii biomass	83.5 a	57.8 a	30.9 c	72.0 a	0.140 ab	2.33 ab
MPR[1] on fallow+ *T. vogelii* biomass	81.4 a	73.3 a	43.2 ab	83.3 a	0.213 a	2.55 ab
T. vogelii biomass+ MPR[2] on maize	80.4 a	76.2 a	48.4 ab	90.4 a	0.220 a	2.88 a

Means bearing the same letter within a column are similar by DMRT at $P \leq 0.05$

[1] MPR applied at fallow establishment in 1999/00 season

[2] MPR applied at maize planting in 2001/02 season

Early planting of *T. vogelii* plants and good rainfall distribution during the relayed fallow (Fig. 3) relative the late planted first experiment (Fig. 2) led to higher survival of *T. vogelii* plants. The first experiment was established on 15 April 2000 while the relayed *T. vogelii* was planted about two weeks earlier on 30 March 2002. In Zambia, Kwesiga *et al.* (1999) also reported improvement in survival of 12-month old *T. vogelii* plants from 51% in a low rainfall year to 84% in a high rainfall year.

4.2.4.2 Plant height

The influence of source and combinations of nutrients on plant height of relayed *T. vogelii* plants at 7 and 11 months is given in Table 22. At 7 months, plant height was lowest in plots treated with *T. vogelii* biomass alone and highest in *T. vogelii* biomass+MPR treated plots. At 11 months, the trend of plant height was similar to that at 7 months. The plant height was significantly increased by fertiliser applications at 7 months but not at 11 months (Table 22). This observation is contrary to the results obtained at the same site in the first experiment. In the first experiment, plant height at 12 months was significantly increased by MPR application (Table 16). Non significant differences in plant heights in 11 months old *T. vogelii* plants between the first and second experiment was probably due to increased Pi-P (Fig. 16) which led to similar foliar P concentration (Table 19).

4.2.4.3 Foliar biomass

The foliar biomass of 11-month old relayed *T. vogelii* plants as influenced by application of different fertilizers is given in Table 22. Foliar biomass was significantly increased by application of TSP+S/A, MPR applied at fallow establishment and by MPR combined with *T. vogelii* biomass. As expected, application of *T. vogelii* alone caused a slight increase in foliar biomass, indicating that it was on an inferior P source compared to MPR and TSP in improving foliar biomass yield of *T. vogelii* plants.

Combined application of MPR with S/A or *T. vogelii* biomass led to significantly higher foliar biomass production than the other treatments. However, the foliar biomass accumulated by relayed *T. vogelii* fallow was very small ranging from 0.095 t ha^{-1} in the control to 0.213 kg ha^{-1} in the plots treated with MPR+S/A. The low amount of foliar biomass accumulated by relayed *T. vogelii* fallow was caused by a wider spacing than that of sole planted *T. vogelii* fallows. The plant spacing of relayed *T. vogelii* fallow was 75 x 60 cm compared to 50 x 50 cm for sole planted *T. vogelii* fallow.

Lower foliar biomass of relayed fallow species relative to sole planted species has also been observed elsewhere. At Kagasa, Rwanda, Balasubramanian and Sekayange (1992) reported that relayed Mucuna in Sweet potato grown for 5-6 weeks produced much less foliar biomass (0.026-0.166 t ha^{-1}) than sole planted Mucuna which produced 4.1 t ha^{-1}.

4.2.4.4 Stem biomass

Stem biomass of 11-month old relayed *T. vogelii* plants as influenced by application of different fertilizers is given in Table 22. The stem biomass was highest and significantly increased by combined application of MPR with SA or *T. vogelii* biomass. Application of *T. vogelii* biomass alone or combined with MPR had no effect on stem biomass. The influence of these two treatments and MPR+S/A or MPR+*T. vogelii* biomass on stem biomass were similar. Natural fallow plots had lower stem biomass than plots treated with MPR+S/A or combined application of MPR applied in 2002 and *T. vogelii* biomass. These observations suggest that external P application is necessary for increasing stem biomass production.

The stem biomass contributed an average of 93% of total biomass accumulated. High accumulation of biomass of *T. vogelii* plants in stems of 56.6% in 6- and 87% in 12- month old plants were also reported by George *et al.* (2002b) in Western Kenya. A review of the potential of improved fallows reported by Drechsel *et al.* (1996) showed increasing proportion of stems with increasing age of fallow species.

4.2.4.5 Effects of MPR on foliar biomass quality of relayed *T. vogelii* plants

The quality of foliar biomass was assessed in terms of N and P concentrations. The effect of applying different fertilizer materials on foliar N and P concentrations and N and P accumulations of relayed *T. vogelii* plants is given in Table 23. The foliar P concentration was significantly increased only by co-applying MPR and *T. vogelii* biomass in 2001/02, but P accumulations were not significantly affected by any treatment. Foliar P concentration but not foliar N concentration was significantly affected by different fertilizer applications. These observations were similar to observation obtained on 12-month old plants when MPR was applied on *T. vogelii* fallow at planting (Table 19).

Table 23. Foliar N and P concentration and uptake of 11-months old relayed *T. vogelii* as influenced by annual and residual MPR applications

Treatments	Concentration of N and P (%)		Accumulation of N and P (kg ha^{-1})	
	N	P	N	P
Control	1.90 a	0.09 b	2.79 a	0.13 a
MPR[2]+SA	2.32 a	0.11 b	5.17 a	0.24 a
T. vogelii biomass	2.31 a	0.10 b	2.21 a	0.10 a
MPR[1] on fallow+*T. vogelii* biomass	2.29 a	0.10 b	4.82 a	0.21 a
T. vogelii biomass+MPR[2] on maize	2.32 a	0.13 a	3.26 a	0.19 a

Means bearing the same letter within a column are similar by DMRT at $P \leq 0.05$
[1]MPR applied at fallow establishment in 1999/00 season
[2]MPR applied at maize planting in 2001/02 season

The quality of the biomass of relayed *T. vogelii* plants in terms of foliar N concentration was lower than that of *T. vogelii* plants established in the 1999/00 season. Foliar N concentrations of relayed *T. vogelii* plants ranged from 1.9 to 2.32% while for the fallow established in 1999/00 at the same site was from 2.8 to 3.0% (Table 19). The differences in foliar N concentrations between the two fallows were probably caused by either contrasting seasonal effects or seed bed preparation. Leaf sampling of relayed *T. vogelii* plants was done during the dry season, while in the first fallow experiment, it was in the wet season. The foliar N concentrations of samples collected in the wet season in the first fallow experiment were also significantly higher than for samples collected in the dry season (Fig. 7). Moisture stress reduces N_2-fixation and overall performance of N_2-fixing legumes (Abebe, 1994), with larger amounts of N_2-fixed in the long rainy season than in the dry season (Giller and Wilson, 1991).

Variation in seed-bed preparation may also have contributed to differences in behaviour of the two *T. vogelii* fallows. In the first experiment, planting holes were dug to a depth 30 cm, while in the second experiment the depth of loose soil was only 15 cm. The loose soil of up to 30 cm depth may have increased aeration and root penetration than that in 15 cm depth. According to Giller and Wilson (1991), soil disturbance stimulates plant growth through better aeration in the soil and increased microbial activities.

4.2.4.6 Relationship between various *T. vogelii* plant parameters and Pi-P

Simple correlation analysis was used to establish the relationship between *T. vogelii* plant parameters and Pi-P. Table 24 gives correlations between foliar biomass and Pi-P, foliar N and P concentrations. Foliar biomass was significantly correlated with Pi-P ($r = 0.92$), but not with foliar N and P concentrations.

Table 24. Correlations between foliar biomass and Pi-P, foliar N and P concentrations

Parameter	Correlation coefficient (r) (df = 4)	Significance
Pi-P *vs* foliar biomass	0.92	**
Foliar P conc. *vs* foliar biomass	0.73	ns
Foliar N conc. *vs* foliar biomass	0.81	ns

ns non significant.
** significant at 1%

The correlations between Pi-P and, foliar N and P concentrations and uptakes are given in Table 25. Foliar P accumulation was significantly correlated with Pi-P (r = 0.86) but foliar N concentration and accumulation, and foliar P concentrations were not. The data (Tables 24 and 25) indicate that available P is very important for improvement of foliar P and biomass accumulations in acid P deficient Ferralsols.

Table 25. Correlations between Pi-P and foliar N and P concentrations and accumulations

Parameter	Correlation coefficient (r) (df = 4)	Significance
Foliar P accumulations *vs* Pi-P	0.86	*
Foliar P concentrations *vs* Pi-P	0.70	ns
Foliar N concentrations *vs* Pi-P	0.72	ns
Foliar N accumulations *vs* Pi-P	0.75	ns

ns non significant
* significant at 5%

The data generated suggest that relaying *T. vogelii* plants with maize can improve survival and plant height of the fallow species. In the sub humid climate and on acid P deficient Ferralsols of SUA farm in Morogoro, the foliar biomass of one year *T. vogelii* fallow relayed with maize accumulated only 3-5 kg N- and 0.2 kg P- ha^{-1}. In addition 11-month old *T. vogelii* stems (Table 22) can be used to complement the low N and P accumulated in the leaves but both sources cannot provide sufficient N for subsequent maize crop. The proportion of stem of *T. vogelii* plants increase with age up to 12 months (George *et al.*, 2002b). Due to this behaviour, improved *T. vogelii* fallow requires a longer period of more than 12 months in the field for production of foliar biomass as litterfall for sufficient N accumulation for subsequent cropping in Eastern Tanzania.

4.3 Dynamics of Selected Nutrients in Soils

4.3.1 Influence of MPR application on decomposition of *T. vogelii* leaves and N release

The aim of this incubation study was to assess the influence of combined application of *T. vogelii* leaves and MPR to a Ferralsol on mass loss of *T. vogelii* leaves and N release pattern.

The decomposition expressed as proportions of the original mass and N contents applied to that remaining in the retrieved materials are presented in Figures 8 and 9. Appendix 8 gives N concentrations of *T. vogelii* residues at each retrieval time. Generally, the proportion of mass loss of *T. vogelii* leaves and N contents as influenced by MPR application in 84 days of incubation had three phases. Phase I occurred during the first 14 days and was characterized by a higher rate of decomposition than the other two phases. Phase II occured during 14 to 56 days and was characterized by relatively slower decomposition rate than that in phase I. Phase III occurred during 56 and 84 days and was characterized by relatively faster decomposition rate than that in phase II but slower than in phase I. Minjingu PR application significantly increased mass loss of *T. vogelii* leaves in the first 14 and 28 days. Application of MPR led to losses of 32.8 and 48% in the first 14 and 28 days, respectively. The corresponding mass losses in soils without MPR were 29.2 and 42.8%.

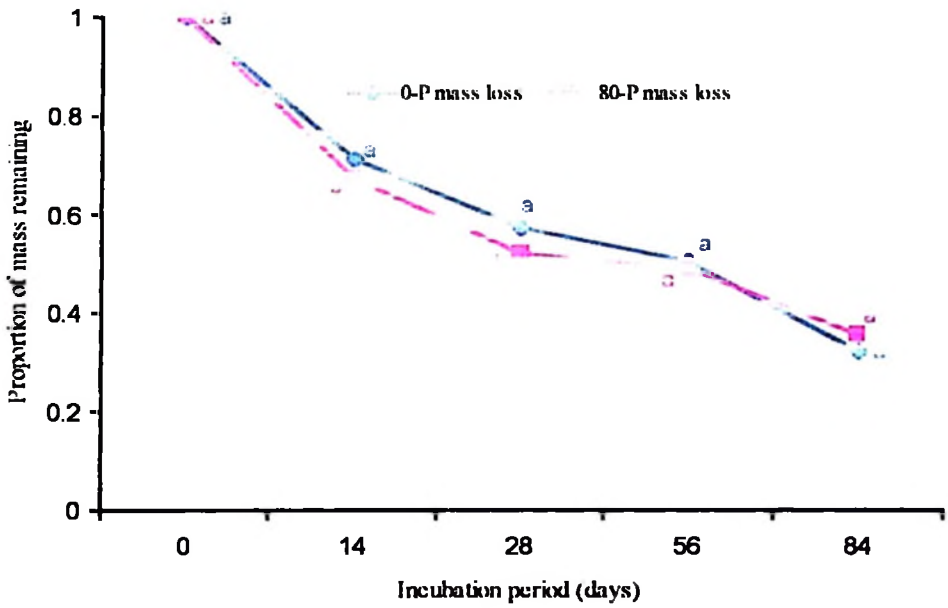


Figure 8. Influence of MPR application on mass loss from *T. vogelii* leaves

Over the 84 days of incubation, N released was not influenced by MPR application. The mean mass loss of *T. vogelii* leaves in phases I, II and III were 31, 17 and 19%, respectively. The corresponding N released was 48, 10 and 11%. This observation indicates that the largest N release occurs during the first 14 days where about 31% of the material had been decomposed. Thereafter, the decomposition slowed down so that at 56 days of incubation another 17% had been decomposed. This means that *T. vogelii* leaves released almost 50% of its N before high maize N demand. High N demand in maize increases with age and ends just before tasselling stage of growth (Mengel and Kirkby, 1982).

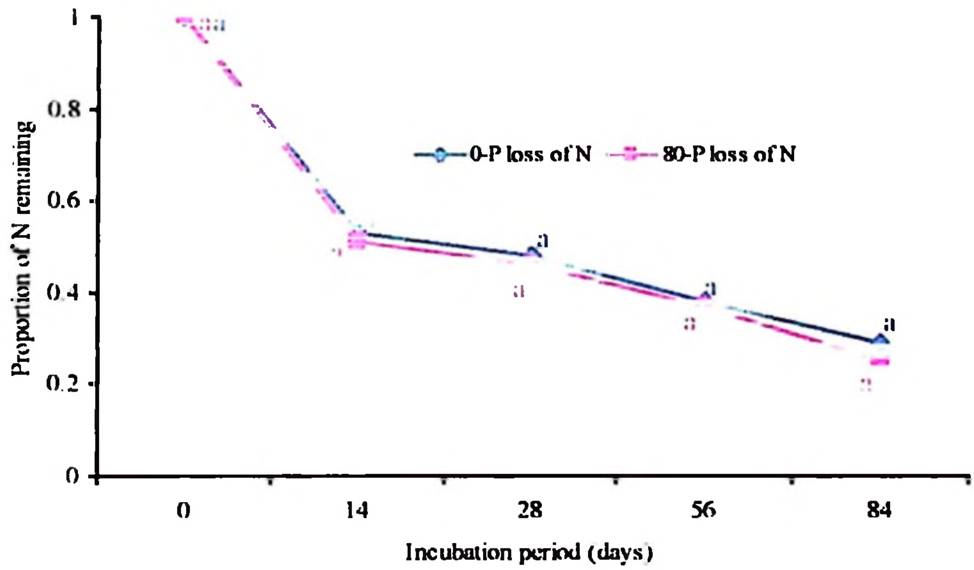


Figure 9. Influence of MPR application on N loss from *T. vogelii* leaves

This study indicated that application of MPR significantly modified the rate of decomposition of *T. vogelii* leaves at least during the initial 28 days. However, the litter bag and compaction of *T. vogelii* leaves could have created different microclimates and the results obtained in this study could be different from unconfined litter or soil incorporated biomass in the field.

Initial rapid decomposition of *T. vogelii* leaves releasing 33 and 58% of N in 7 and 28 days, respectively was also observed by Fasuluku (1998). Relative to the leaves of other species, *T. vogelii* leaves decomposes at relatively slower rate. Palm *et al.* (1988)

reported that 71% of *S. sesban* leaves were decomposed in the first 14 days. *Leucaena leucocephala* and *C. siamea* mulch released 80-85% of N in the first 14 days (Jama and Nair, 1996). Faster initial decomposition of *T. vogelii* leaves is due to its narrower C:N ratio of 13. Plant materials with C:N ratio < 30 are likely to decompose more rapidly with net N mineralization occurring right from the beginning (Giller and Wilson, 1991).

4.3.2 Influence of combined application of *T. vogelii* leaves with MPR on Pi-P

Influence of combined application of *T. vogelii* leaves with MPR on Pi-P is given in Fig. 10. At all the sampling dates, Pi-P was not affected by application of *T. vogelii* leaves (Appendix 9). However, application of MPR alone or with *T. vogelii* leaves significantly increased Pi-P. The Pi-P in soil applied with MPR alone or combined with *T. vogelii* leaves were similar at day 1 to 14, but MPR alone gave significantly higher Pi-P thereafter. Addition of *T. vogelii* leaves to MPR depressed Pi-P. Calcium contained in the *T. vogelii* leaves might have increased soil solution and exchangeable Ca, hence decreasing MPR dissolution (equation 2).

The biomass of *T. vogelii* applied contained a total of 60.6 mg Ca kg^{-1} in addition to 160 mg Ca kg^{-1} added by MPR (Table 9). This is an increase of 27% above that added by MPR alone. Smithson (1999) reported that combined application of MPR with *Tithonia diversifolia* biomass depressed resin P. *Tithonia diversifolia* biomass contributed 25% more Ca in the system compared to application of MPR alone. Immobilization of P during decomposition of *T. vogelii* leaves might have also contributed to decreasing MPR dissolution.

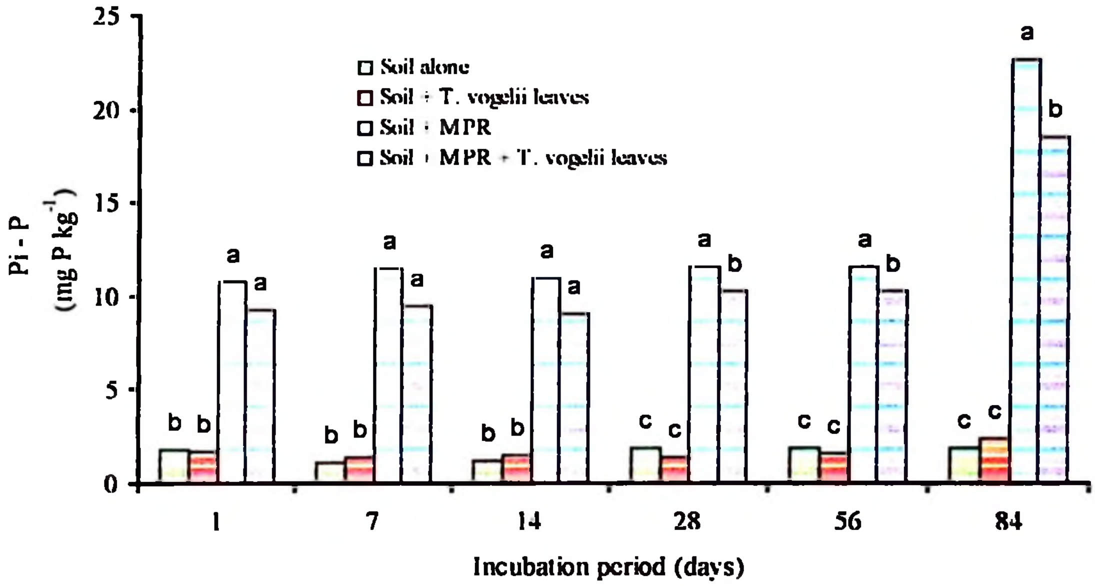


Figure 10. Influence of applying *T. vogelii* leaves and MPR on Pi-P

This study has shown that in strongly acid P deficient Ferralsol, the influence of inherent soil conditions such as low P and strong acidity (pH < 5.5) on P availability from MPR is higher than that caused by the chemical composition of *T. vogelii* biomass.

4.3.3 Pi-P at maize harvesting

The Pi-P contents of soil samples collected at maize harvesting in the glasshouse study are given in Fig. 11. The Pi-P values were significantly increased by application of TSP+S/A, MPR alone or combined with either S/A or *T. vogelii* leaves (Appendix 10). Application of *T. vogelii* leaves increased Pi-P values slightly. The Pi-P values were statistically similar in pots treated with TSP+S/A, MPR alone or combined with either S/A or *T. vogelii* leaves, implying that all these treatments increased labile P.

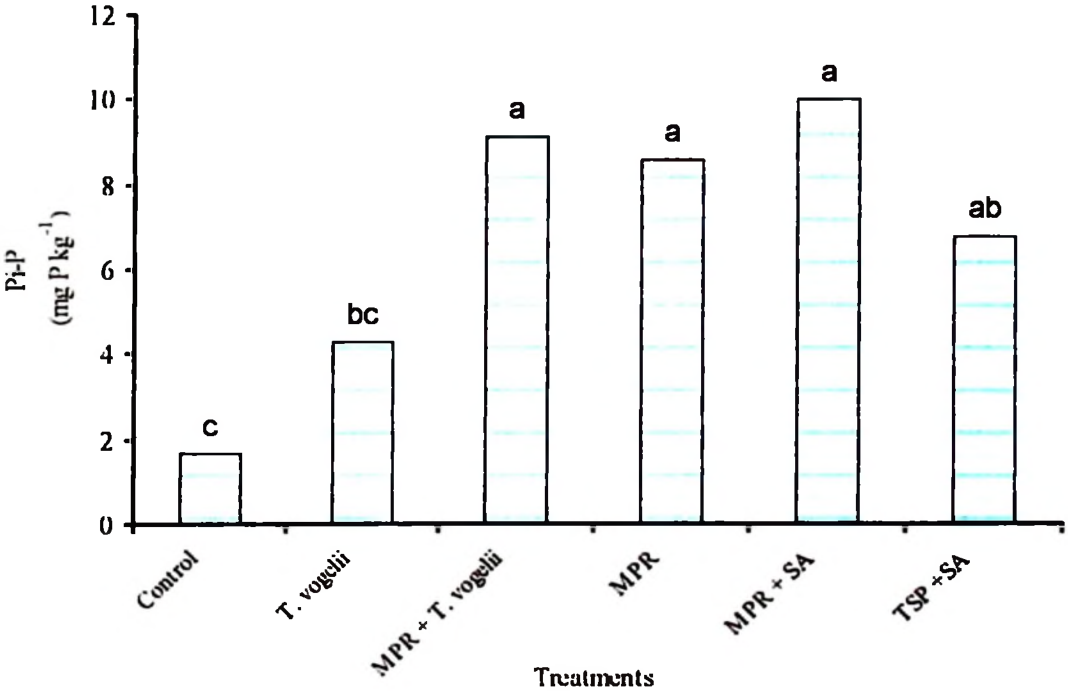


Figure 11. Influence of combined application of MPR with *T. vogelii* leaves on Pi-P in different treatments at maize harvesting.

Higher Pi-P values in soils to which MPR was applied was due to increased P availability resulting from inherent soil factors known to enhance MPR dissolution, such as low P, low pH and plant P uptake (Khasawneh and Doll 1978; Rajan *et al.*, 1996). According to the law of mass action (equation 2), the pH gradient and low soil P of the soil used and P uptake by maize plants provided sinks which enhanced P release from MPR treated pots. Slightly lower Pi-P values in soil amended with TSP+SA than in treatments with MPR was probably due to significantly higher P uptake from TSP

(Table 28). These results also indicate that MPR had slightly higher residual Pi-P values than TSP.

4.3.4 Total inorganic N in the fallows

Total inorganic N concentrations were monitored in the fallows in two contrasting seasons: dry season when the fallows were 16 months old and at the onset of the rainy season (at 22 months), while Pi-P was determined only at the onset of the rainy season (at 22 months).

Fig. 12 presents the total inorganic-N concentrations as influenced by fallow type and MPR application in the dry season of 2000/01. Mineral NO_3^- and NH_4^+-N values at each sampling date are given in Appendix 12. In the topsoil, total inorganic-N concentrations were significantly influenced by fallow type, MPR application and soil depth. Total inorganic-N concentrations were significantly higher in *T. vogelii* fallows than in NF plots, with even higher concentrations in *T. vogelii* fallows amended with MPR at establishment than in other fallows.

Larger total inorganic-N values in *T. vogelii* fallows was attributed to decomposition and N mineralization of dead fine roots and nodules, commonly found in larger quantities in the topsoil. Total inorganic-N concentrations in subsoil were significantly lower than in the topsoil. Application of MPR at establishment of *T. vogelii* fallows led to slight improvement in total inorganic-N concentrations, suggesting that there were low organic matter contents in the subsoil.

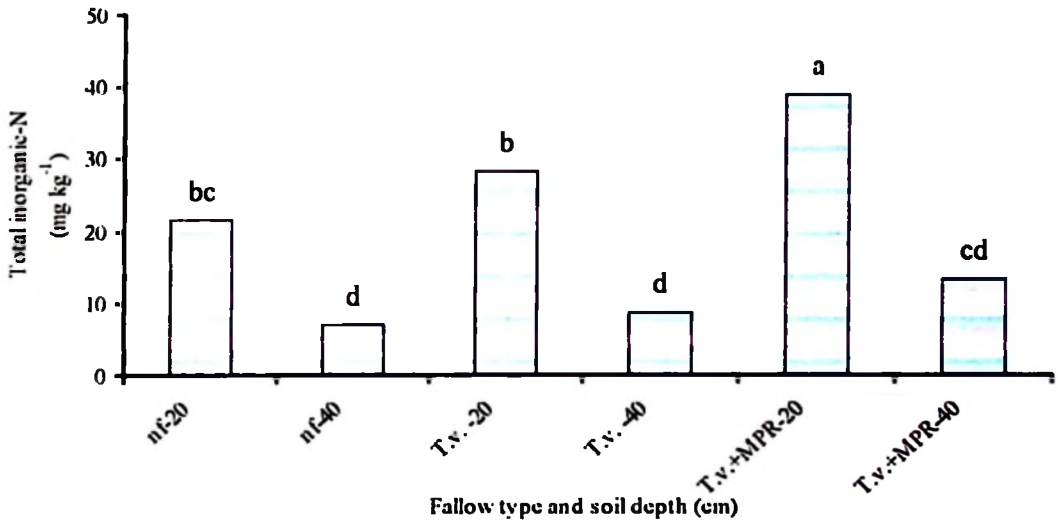


Figure 12. Total inorganic-N in *T. vogelii* fallows during dry season as influenced by MPR application

Legend:

nf-20	Natural fallow at 0-20 cm depth
nf-40	Natural fallow at 20-40 cm depth
T.v.-20	*T. vogelii* fallow at 0-20 cm depth
T.v.-40	*T. vogelii* fallow at 20-40 cm depth
T.v.+MPR-20	*T. vogelii* amended with MPR at 0-20 cm depth
T.v.+MPR-40	*T. vogelii* amended with MPR at 20-40 cm depth

At 22 months, total inorganic-N increased in both fallow types and at various soil depths (Fig. 13). The increases ranged from 1.4 to 1.5-fold in the topsoil and from 4.3 to 4.6-fold in subsoil relative to total inorganic-N values obtained in the dry season (Appendix 11). In the topsoil, total inorganic-N concentrations were slightly higher in *T. vogelii* fallows, and similar regardless of the MPR application status. In the subsoil, total inorganic-N values were slightly increased in *T. vogelii* fallows, but application of MPR at establishment of *T. vogelii* led to significantly higher values.

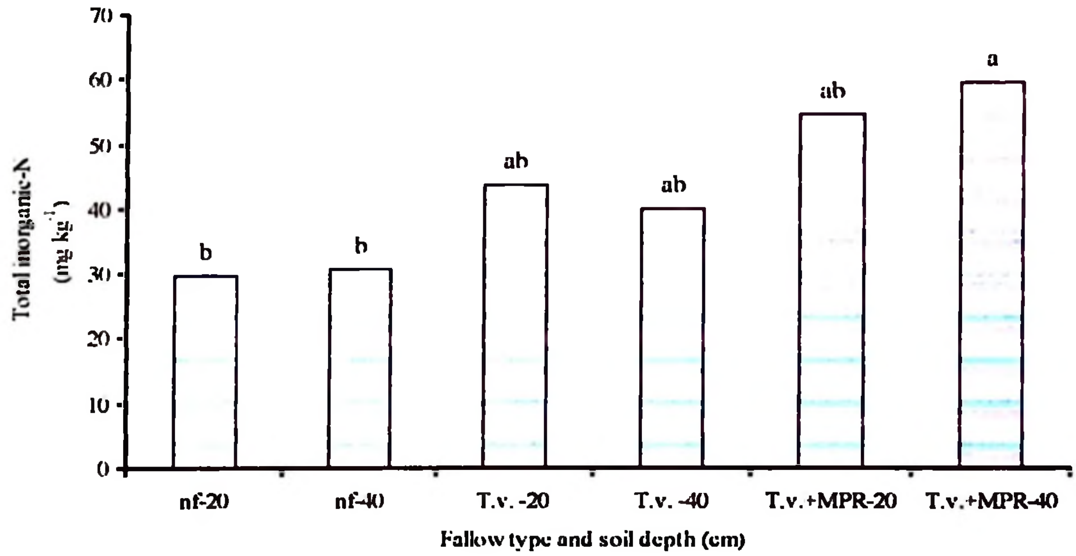


Figure 13. Total inorganic-N in the fallows at the beginning of 2001/02 long rains as influenced by MPR application

Legend:

nf-20	Natural fallow at 0-20 cm depth
nf-40	Natural fallow at 20-40 cm depth
T.v.-20	*T. vogelii* fallow at 0-20 cm depth
T.v.-40	*T. vogelii* fallow at 20-40 cm depth
T.v.+MPR-20	*T. vogelii* amended with MPR at 0-20 cm depth
T.v.+MPR-40	*T. vogelii* amended with MPR at 20-40 cm depth

Increases in total inorganic-N values in the 0-20 cm depths was due to enhanced mineralization of organic matter caused by rewetting of dry soil, whereas in the 20-40 cm depths the increase was probably due to leaching from the topsoil. Under natural conditions, *T. vogelii* fallows substantially increased total inorganic-N relative to NFs, and that MPR application at fallow establishment increased total inorganic-N concentrations slightly further. Rapid increase in total inorganic-N concentrations in *T. vogelii* fallows at the onset of the first rains was also reported in Rwanda by Hagedorn *et al.* (1997). The total inorganic-N concentrations in the topsoil were 20 and 52 kg ha^{-1} during dry season and at the onset of the rains, respectively (Hagedorn *et al.*, 1997).

4.3.5 Pi-P in the fallows

The influence of MPR application at establishment of *T. vogelii* fallows on Pi-P measured at the end of 22 months is given in Table 26. The Pi-P concentrations were significantly increased in the *T. vogelii* fallows that were amended with MPR at planting. The Pi-P values in the natural- and *T. vogelii* fallows that were not amended with MPR were similar.

Table 26. Influence of MPR application at establishment of *T. vogelii* fallows on Pi-P at 22 months

Fallow type	Pi-P (mg P kg^{-1})
Natural fallow	0.98 b
T. vogelii	1.20 b
T. vogelii+MPR	8.44 a

Means bearing the same letter are similar using DMRT at $P \leq 0.05$.

Increased Pi-P values in *T. vogelii* fallows amended with MPR at establishment could be due to soil and plant related factors. Bolan and Hedley (1990) reported that the amount of P dissolved from PRs increased with decreasing soil pH. Plants influence PR dissolution by increasing Ca uptake (Rajan *et al.*, 1996). The increase in Pi-P values in

T. vogelii fallows that was not treated with MPR at establishment could be due to mineralization of organic P. In a rhizopot study, George *et al.* (2002a) reported that available P was increased by 38% and organic P was decreased from 49.7 to 16.8 $\mu g\ g^{-1}$ in the rhizosphere of *T. vogelii* plants. The increase in Pi-P values in *T. vogelii* fallows that were not treated with MPR at establishment was however small and could lead to little effect on subsequent cropping.

Increases in available P under fallows of *T. vogelii* and other leguminous species have been reported elsewhere (Rao *et al.*, 1998; Mgangamundo, 2000). The average increase in available P under short- and long-term woodlot plantations, irrespective of whether the trees were N_2-fixing was 1.1-fold (Montagnini and Sancho, 1990).

4.3.6 Total inorganic-N during the first post-fallow maize

Total inorganic-N concentrations in all the treatments were monitored during the growing season through analysis of surface (0-15 cm depth) soils samples at planting, at 35 days after planting and at 45 days after planting.

The results for total inorganic-N concentrations as influenced by applications of fallow biomass and MPR (residual and current) in maize relayed with *T. vogelii* plants in 2001/02 season are presented in Fig. 14. Corresponding NO_3^-- and NH_4^+-N concentrations are given in Appendix 14.

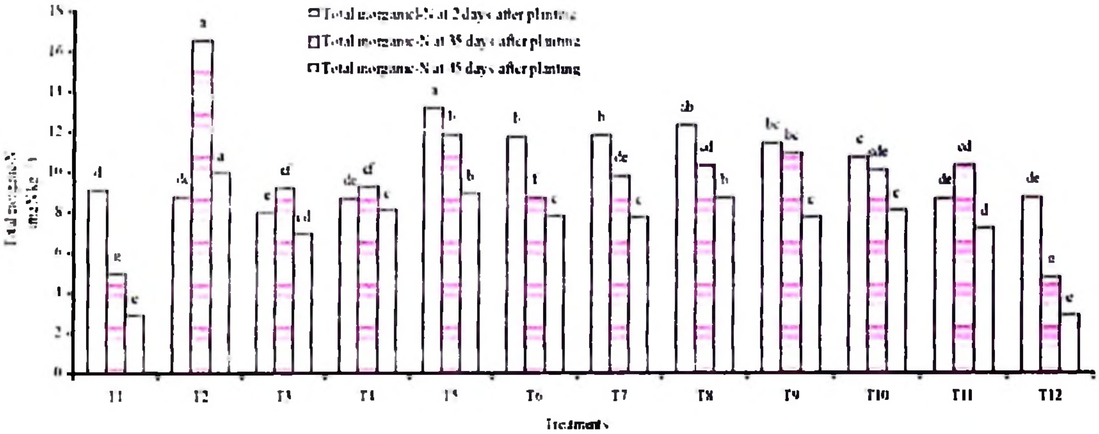


Figure 14. Influence of combined application of MPR with *T. vogelii* biomass on total inorganic-N in the maize field experiment during 2001/02 season (means were compared for each sampling date)

Legend:

T1	Natural fallow biomass applied at maize planting (2001/02)
T2	S/A (80 kg N ha^{-1}) applied at maize planting (2001/02. 2002/03)
T3	TSP (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T4	MPR (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T5	*T. vogelii* biomass (80 kg N ha^{-1}) applied at maize planting (2001/02)
T6	*T. vogelii* biomass (80 kg N ha^{-1})+MPR applied at *T. vogelii* fallow establishment (1999/00)
T7	*T. vogelii* biomass+ combined with MPR at maize planting (2001/02)
T8	Treatment 5+*T. vogelii* relay after maize planting (2001/02)
T9	Treatment 6+*T. vogelii* relay after maize planting (2001/02)
T10	Treatment 7+*T. vogelii* relay after maize planting (2001/02)
T11	Treatment 4+*T. vogelii* relay after maize planting (2001/02)
T12	Treatment 1+*T. vogelii* relay after maize planting (2001/02)

At two days after planting which was five days after incorporation of fallow biomass, total inorganic-N concentrations were significantly affected by MPR and *T. vogelii* fallow biomass applications. The total inorganic-N concentrations, ranging from 12.4-13.2 mg kg^{-1} (Appendix 13) were significantly higher in plots that were under *T. vogelii* fallows and applied with its biomass than in other treatments. Application of MPR at fallow establishment or combined with *T. vogelii* biomass significantly reduced total inorganic-N concentrations. The total inorganic-N concentrations in *T. vogelii* fallows plots that were amended with MPR at fallow establishment ranged from 10.8-11.8 mg kg^{-1} (Appendix 13). Application of NF biomass led to significantly lower total inorganic-N concentrations than in the treatments applied with *T. vogelii* fallow biomass. Lower total inorganic-N concentrations in the treatments applied with NF biomass than in the *T. vogelii* fallow biomass treated plots could be attributed to lower N concentrations and wider C:N ratio of the NF biomass (Appendix 3). According to Giller and Wilson (1991), the plant materials with C:N ratios of < 30 are likely to mineralize right from the beginning. The C:N ratio of *T. vogelii* fallow biomass was 13.

At 35- and 45-days after planting, total inorganic-N concentrations in plots treated with *T. vogelii* fallow biomass were significantly higher than in plots treated with NF biomass. Application of S/A alone as expected significantly increased total inorganic-N concentrations at both 35- and 45-days after planting. Combined application of MPR with either S/A or *T. vogelii* biomass or TSP with S/A led to significant depression of total inorganic-N concentrations throughout the three sampling dates. This observation suggests that increased P availability and uptake by maize led to higher N uptake. In a field experiment conducted in semi-arid zone of Eastern Kenya using sorghum as a test crop, Warren *et al.* (1997) reported that P application depressed NO_3^--N concentrations due to increased plant uptake of this nutrients. This study has shown that in N and P deficient soils, higher rates of both nutrients should be applied.

The total inorganic-N concentrations in all the treatments were generally higher at the beginning of the rainy season, decreased as rainy season progressed and were lowest towards the end of the season. Relaying *T. vogelii* plants four weeks after maize planting had no effect on the total inorganic-N concentrations. This is because soil sampling was done when *T. vogelii* plants were still young to have any effect on total inorganic-N concentrations.

Higher total inorganic-N concentrations at five days after incorporation of biomass (preceded by a heavy rainstorm two days before soil sampling) could be associated with initial rapid decomposition and N release of the fallow biomass (Fig. 13). Gradual decrease in total inorganic-N concentrations with increase in time from planting could be caused by increased maize N uptake and leaching losses. In a field experiment, involving *T. vogelii* biomass, sorghum residues and NF biomass in South Rwanda, Hagedorn *et al.* (1997) observed that an N flush occurred during the first 5 days of the rainy season that doubled the mineral N concentrations. Leaching of total inorganic-N from *T. vogelii* biomass and sorghum residues was highly correlated ($r^2 = 0.94$) to mineralized N at the beginning of the rainy season (Hagedorn *et al.*, 1997). Prescott (1997) reported that soil moisture is a more critical factor for mineralization than temperature. The rate of N release from *G. sepium* and *L. leucocephala* pruning was reduced by inadequate moisture (Handayanto *et al.*, 1994).

At all the three sampling dates, total inorganic-N concentrations in plots treated with *T. vogelii* biomass alone or combined with MPR were consistently higher than in plots treated with NF biomass (Fig. 14). This was probably caused by slow rate of N release and high N concentrations of the decomposing residues of *T. vogelii* biomass. In the decomposition study, the leaves of *T. vogelii* released 48% of its N in the first 14 days, and thereafter the release was slower (Fig. 9). On the 84th day of incubation, *T. vogelii* residues contained 2.4% N (Appendix 8), indicating that the biomass has the potential to continue supplying N subsequent to 84th day. The pronounced effect of *T. vogelii* leaves on maintaining total inorganic-N throughout the rainy season relative to NF was also reported by Hagedorn *et al.* (1997) in Rwanda.

According to Shapiro *et al.* (2001), NO_3-N concentrations of < 1, 1-3 and 3-9 mg kg^{-1} are classified as very low, low and medium levels, respectively. Based on this categorization, *T. vogelii* fallow biomass provided NO_3-N concentrations which fell in the medium level throughout the cropping season. The concentrations of NO_3-N in the NF plots were medium only at the onset of the rainy season, but declined to low as the cropping season progressed. Application of S/A at 2 and 4 weeks after planting, maintained NO_3-N concentrations in the medium class throughout the cropping season (Appendix 14) as expected.

4.3.7 Pi-P in the first post-fallow maize

The Pi-P values in all the treatments were determined during the growing season through analysis of soil samples collected at 45 days after maize planting. The effect of MPR application at establishment of *T. vogelii* fallow or MPR combined with *T. vogelii* biomass at maize planting on Pi-P at 45 days after maize planting is presented in Fig. 15. The Pi-P values were significantly affected by the two MPR application strategies. Application of MPR at *T. vogelii* fallow establishment followed by fallow biomass application (T6) led to a slight increase in Pi-P values relative to combined application of MPR with fallow biomass at maize planting (T7).

The Pi-P values were significantly increased by application of *T. vogelii* biomass alone (T5) compared to NF biomass (T1). Application of TSP+S/A (T3) gave significantly higher Pi-P values than that of MPR+S/A (T4). The treatment which received MPR at fallow establishment and *T. vogelii* biomass at planting in 2001/02 (T6) had Pi-P values comparable to that in MPR+S/A treatment. Application of MPR+S/A (T4) led to slightly higher Pi-P values than that of MPR+*T. vogelii* biomass (T7). Inclusion of *T. vogelii* as relay in the treatments 8-12 had no effect on Pi-P values at least during young stage of relayed *T. vogelii* plants.

Increased Pi-P values by MPR application at fallow establishment could be caused by both soil and plant related factors. In the case of soil related factors, the soil at the site was strongly acid and inherently low in P (Table 6). Strong soil acidity and low

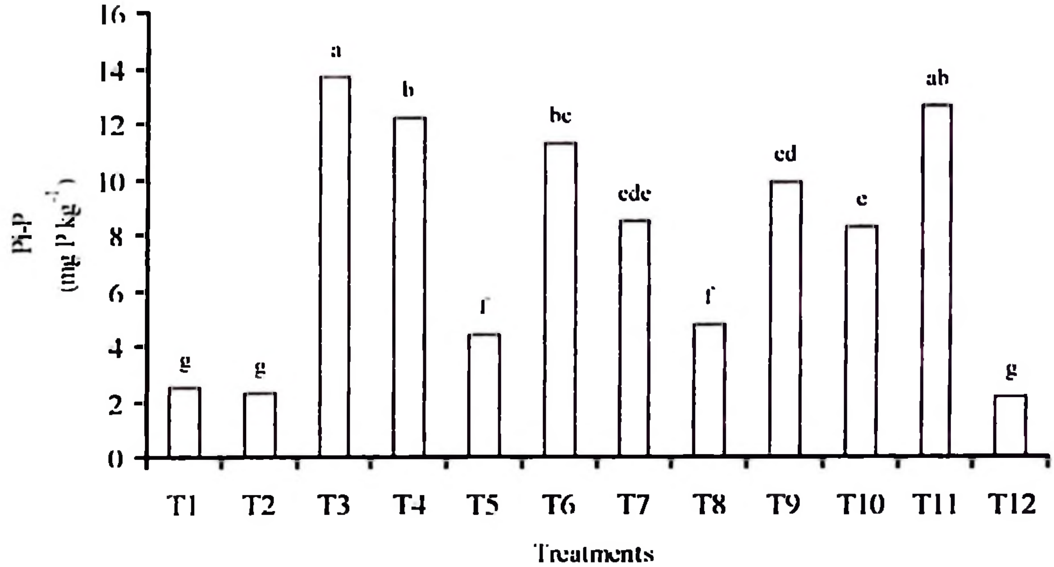


Figure 15. Influence of MPR application to *T. vogelii* fallows and combined application of MPR with fallow biomass on Pi-P in 2001/02 season

Legend:

T1	Natural fallow biomass applied at maize planting (2001/02)
T2	S/A (80 kg N ha^{-1}) applied at maize planting (2001/02, 2002/03)
T3	TSP (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T4	MPR (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T5	*T. vogelii* biomass (80 kg N ha^{-1}) applied at maize planting (2001/02)
T6	*T. vogelii* biomass (80 kg N ha^{-1})+MPR applied at *T. vogelii* fallow establishment (1999/00)
T7	*T. vogelii* biomass+ combined with MPR at maize planting (2001/02)
T8	Treatment 5+*T. vogelii* relay after maize planting (2001/02)
T9	Treatment 6+*T. vogelii* relay after maize planting (2001/02)
T10	Treatment 7+*T. vogelii* relay after maize planting (2001/02)
T11	Treatment 4+*T. vogelii* relay after maize planting (2001/02)
T12	Treatment 1+*T. vogelii* relay after maize planting (2001/02)

P levels favour MPR dissolution (Mnkeni *et al.*, 1991). Enhancement of Pi-P concentration in plots amended with MPR at fallow establishment could also be due to Ca and P uptake by *T. vogelii* and maize plants. Increased Ca and P uptake by these plants could have caused greater MPR dissolution. Application of MPR at fallow establishment led to 3-fold increase in total P accumulated by *T. vogelii* plants relative to the control (Table 21).

The Pi-P values in plots that were treated with MPR at establishment of *T. vogelii* fallow then followed by application of fallow biomass were significantly higher than that in NF. Higher Pi-P values in plots that were treated with MPR at fallow establishment was caused by increased Pi-P values during the fallow period (Table 26) and P released from decomposing *T. vogelii* biomass (Fig. 15). The Pi-P data for the 2001/02 season suggest that application of MPR at fallow establishment is a better strategy than combined application of MPR with *T. vogelii* biomass at maize planting.

4.3.8 Total inorganic-N in the second post-fallow maize

Total inorganic-N in all the treatments were monitored during the growing season through analysis of surface (0-15 cm depth) soils samples collected at 13- and 54- days after planting.

The results for total inorganic N concentrations for 2002/03 season as influenced by previously applied MPR, TSP and *T. vogelii* biomass and freshly applied S/A and *T. vogelii* biomass are presented in Fig. 16. Appendix 17 gives mineral-N as NO_3^-- and NH_4^+-N concentrations in the two sampling dates. At 13 days after planting, the total inorganic-N concentrations were higher following long dry spells which occurred

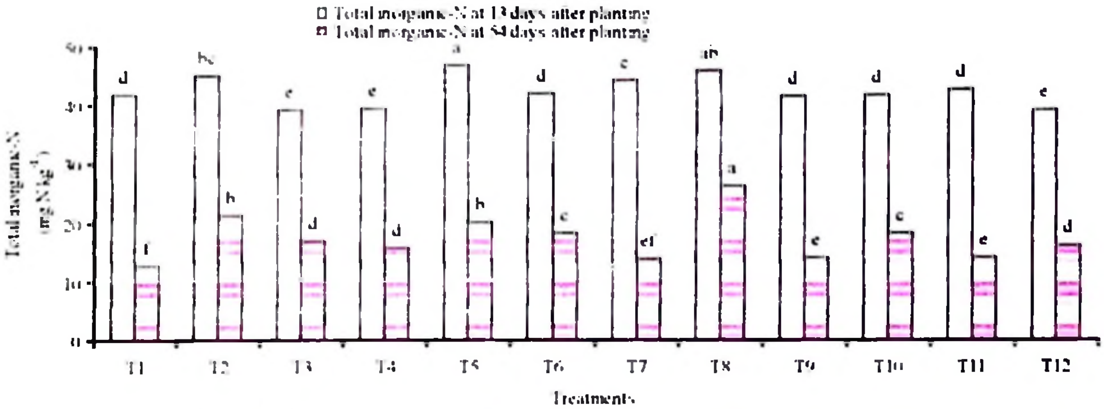


Figure 16. Effects of freshly applied *T. vogelii* biomass and residual biomass and MPR on total inorganic-N concentrations in different treatments in the maize experiment in 2002/03 season

Legend:

T1	Natural fallow biomass applied at maize planting (2001/02)
T2	S/A (80 kg N ha^{-1}) applied at maize planting (2001/02, 2002/03)
T3	TSP (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T4	MPR (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T5	*T. vogelii* biomass (80 kg N ha^{-1}) applied at maize planting (2001/02)
T6	*T. vogelii* biomass (80 kg N ha^{-1})+MPR applied at *T. vogelii* fallow establishment (1999/00)
T7	*T. vogelii* biomass+combined with MPR at maize planting (2001/02)
T8	Treatment 5+*T. vogelii* relay after maize planting (2001/02)
T9	Treatment 6+*T. vogelii* relay after maize planting (2001/02)
T10	Treatment 7+*T. vogelii* relay after maize planting (2001/02)
T11	Treatment 4+*T. vogelii* relay after maize planting (2001/02)
T12	Treatment 1+*T. vogelii* relay after maize planting (2001/02)

between short rainfall events (Appendix 4). Relative to control, the total inorganic-N concentrations were significantly lower in soils that were treated with TSP+S/A (T3) or MPR+S/A (T4) in the 2001/02 season. The total inorganic-N was significantly greater in plots that were previously treated with *T. vogelii* biomass (T5 and T7), but were significantly smaller due to addition of fresh biomass (T9 and T10). Lower total inorganic-N levels in plots to which a first dose of *T. vogelii* biomass (T9 and T10) was applied, were probably caused by low decomposition of *T. vogelii* biomass due to lack of sufficient moisture

At 54 days after planting, total inorganic-N concentrations were lower relative to the levels observed at 13 days after planting (Appendix 16). Previous applications of *T. vogelii* biomass led to significant increase in total inorganic-N concentrations (T5 and T6). Addition of fresh biomass on previously applied *T. vogelii* biomass (T8, T9 and T10) also significantly increased total inorganic-N concentrations, suggesting that *T. vogelii* biomass applied previously continued supply inorganic-N.

However, at both sampling dates there were some inconsistencies of total inorganic-N levels in soils to which the same amount of *T. vogelii* biomass was applied. Apparent inconsistencies observed were probably hastened by the occurrence of long dry spells between short rainfall events experienced during the 2002/03 rainy season (Appendix 4).

Enhancement of N mineralization after wetting has long been recognized (Birch, 1960) and is being reported widely (Hagedorn *at al.*, 1997; Warren *et al.*, 1997). The inorganic N flushes occur in soils with a pronounced change from dry to wet season (Birch, 1960; De Bruin *et al.*, 1989). At Machang'a in Kenya, Warren *et al.* (1997) reported total inorganic-N concentrations of 12, 7 and 5 mg N kg^{-1} after the first, second and third rainfall events, respectively. The rainfall intensities were 30 mm for first, 50 mm for second and 32 mm for third rainfall events. At Rubona Rwanda, total inorganic-N concentrations were 52, 42 and 14 kg N ha^{-1} after the first, second and third rainfall events of 25, 40 and 80 mm, respectively (Hagedorn *et al.*, 1997).

Despite the long dry spells between short rainfall events which affected mineralization, the data generated indicate that *T. vogelii* biomass applied in the previous season has a significant effect on total inorganic-N at least at the beginning of the season. The effect decreased mineral-N substantially as the season progressed. Fresh application of the biomass to plots that were previously treated with *T. vogelii* biomass significantly increased total inorganic-N later in the season, and could thus offset the problem of decreasing total inorganic-N concentrations at vegetative and tasselling stages of maize growth when demand for N is high. Combined application of *T. vogelii* biomass or S/A with MPR or TSP decreased total inorganic-N concentrations with no effect on the year of P application and P sources.

4.3.9 Pi-P in the second post-fallow maize

The Pi-P values in all the treatments were determined during the growing season through analysis of soil samples collected at 54 days. In the 2002/03 season, the trend of Pi-P was different from that for 2001/02 season (Figures 15, 17). Generally, the concentrations of Pi-P decreased in all the treatments relative to the levels in 2001/02. This was due to high P uptake by maize plants in both two seasons. Relative to NF plots, the Pi-P values were significantly increased in all the treatments applied with different P sources.

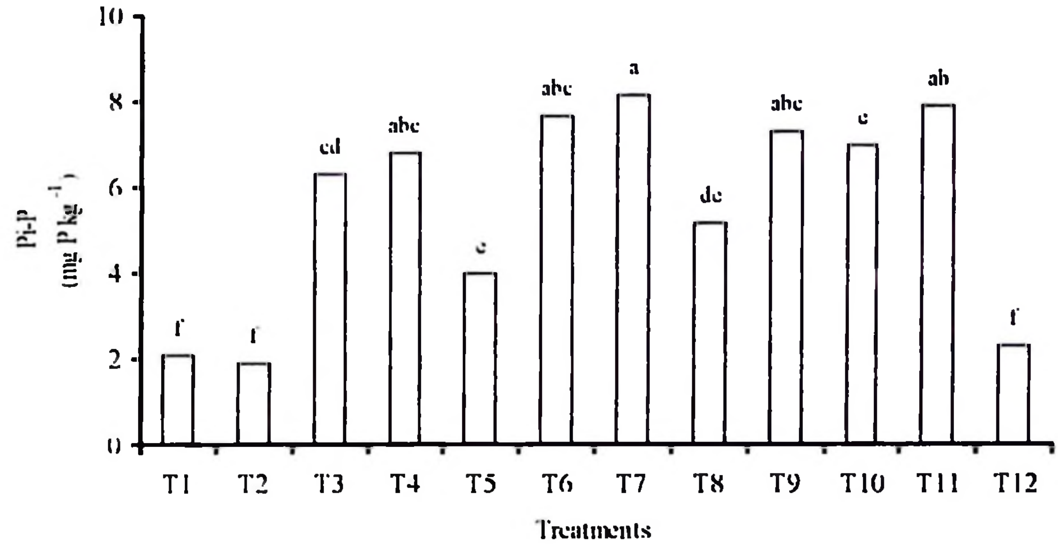


Figure 17. Effects of residual MPR and *T. vogelii* applications on Pi-P in 2002/03 season

Legend:

T1	Natural fallow biomass applied at maize planting (2001/02)
T2	S/A (80 kg N ha^{-1}) applied at maize planting (2001/02, 2002/03)
T3	TSP (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T4	MPR (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T5	*T. vogelii* biomass (80 kg N ha^{-1}) applied at maize planting (2001/02)
T6	*T. vogelii* biomass (80 kg N ha^{-1})+MPR applied at *T. vogelii* fallow establishment (1999/00)
T7	*T. vogelii* biomass+combined with MPR at maize planting (2001/02)
T8	Treatment 5+*T. vogelii* biomass at 30 kg N ha^{-1} applied in 2002/03 season
T9	Treatment 6+*T. vogelii* biomass at 30 kg N ha^{-1} applied in 2002/03 season
T10	Treatment 7+*T. vogelii* biomass at 30 kg N ha^{-1} applied in 2002/03 season
T11	Treatment 4+*T. vogelii* biomass at 30 kg N ha^{-1} applied in 2002/03 season
T12	Treatment 1+*T. vogelii* biomass at 30 kg N ha^{-1} applied in 2002/03 season.

Application of MPR to maize had slightly higher Pi-P of 8.2 mg P g^{-1} compared to 7.7 mg P g^{-1} for soils treated with MPR at fallow establishment. Lower Pi-P concentrations in plots treated with MPR at fallow establishment could be caused by P uptake by both *T. vogelii* and maize plants during four seasons. The P uptake in plots treated with MPR at maize planting was for two seasons only. Application of a second dose of *T. vogelii* biomass at lower rate (30 kg N ha^{-1}) had a significant effect on Pi-P values. The Pi-P values increased in soils treated with a second dose of *T. vogelii* biomass relative to one time application.

Higher residual effects of MPR relative to TSP as observed in this experiment, has been reported by Semoka and Kalumuna (1999) and Mkangwa (2003). Higher residual Pi-P values observed suggests that applying MPR to *T. vogelii* at fallow establishment followed by application of fallow biomass was a relatively better strategy than treating the soil with MPR+S/A applied two years later.

Combined application of MPR with *T. vogelii* biomass seem to be a better approach due to its bigger residual Pi-P values than treating the soil with MPR+S/A. This could be caused by slow P released from organic residues of *T. vogelii* biomass. The residual Pi-P value in the soil treated with *T. vogelii* biomass alone in 2001/02 season was significantly higher than that in the plots where NF biomass was applied. Application of biomass from relayed *T. vogelii* plants appear to be useful in maintaining higher Pi-P values obtained from the first fallow biomass applications.

4.3.10 Changes in soil pH and exchangeable Ca

The change in soil pH and exchangeable Ca in all the treatments were evaluated through analysis of soil samples collected on 10 April 2000 and 30 July 2003, representing the beginning and the end of the field experiments, respectively.

4.3.10.1 Soil pH

The data for soil pH at the beginning and at the end of the field experiments are given in Table 27 Relative to initial soil pH, the final soil pH was significantly higher in the plots treated with MPR combined with *T. vogelii* biomass or S/A. The trend of increasing soil pH was: MPR at fallow establishment followed by application of *T. vogelii* biomass (T6) > MPR combined with *T. vogelii* biomass at maize planting (T7) > MPR+S/A followed by application of *T. vogelii* biomass (T11). Second application of *T. vogelii* biomass on plots that were previously co-applied with MPR and *T. vogelii* biomass also significantly increased soil pH (T10).

Increments in soil pH in MPR combined with *T. vogelii* biomass plots were caused by high Ca contents in both of these fertilizer materials (Tables 8, 25). The increase in pH in soils treated with *T. vogelii* biomass has also been reported elsewhere. In a Ferralsol in Western Kenya, George *et al.* (2002b) reported that 18-month old *T. vogelii* fallows with litter retained increased soil pH by 1.0 pH unit.

4.3.10.2 Exchangeable Ca

Exchangeable Ca values due to fallows, application of fertilizers and maize cropping are given in Table 27. The exchangeable Ca values were significantly increased in all the treatments, except in plots treated with S/A alone. Application of *T. vogelii* biomass alone significantly increased exchangeable Ca values by 2.4 and 3.3 fold for one and two applications, respectively. Application of MPR at *T. vogelii* establishment, followed

Table 27. Effect of applying *T. vogelii* biomass, MPR and maize cropping on changes in soil pH and exchangeable Ca levels

Treatments	Soil pH (H_2O)		Exchangeable Ca ($cmol_c\ kg^{-1}$)	
	10 April 2000	30 July 2003	10 April 2000	30 July 2003
T1	5.6a	5.9a	2.06b	2.65a
T2	5.4a	5.7a	2.25a	2.97a
T3	5.7a	6.2a	2.63b	7.92a
T4	5.7a	6.2a	2.19b	10.00a
T5	5.6a	6.1a	2.66b	6.36a
T6	5.5b	6.2a	2.96b	10.98a
T7	5.7a	6.3a	2.36b	11.96a
T8	5.6a	6.1a	2.41b	8.01a
T9	5.6a	6.1a	2.94b	8.57a
T10	5.5b	6.2a	2.02b	6.76a
T11	5.3a	5.9a	2.41b	8.87a
T12	5.8a	6.1a	2.63b	4.37a

Means with the same letter for the same soil property and within a row are similar using student t-test at $P \leq 0.05$

Legend:

T1	Natural fallow biomass applied at maize planting (2001/02)
T2	S/A (80 kg N ha^{-1}) applied at maize planting (2001/02, 2002/03)
T3	TSP (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T4	MPR (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T5	*T. vogelii* biomass (80 kg N ha^{-1}) applied at maize planting (2001/02)
T6	*T. vogelii* biomass (80 kg N ha^{-1})+MPR applied at *T. vogelii* fallow establishment (1999/00)
T7	*T. vogelii* biomass+combined with MPR at maize planting (2001/02)
T8	Treatment 5+*T. vogelii* biomass at 30 kg N ha^{-1} applied in 2002/03 season
T9	Treatment 6+*T. vogelii* biomass at 30 kg N ha^{-1} applied in 2002/03 season
T10	Treatment 7+*T. vogelii* biomass at 30 kg N ha^{-1} applied in 2002/03 season
T11	Treatment 4+*T. vogelii* biomass at 30 kg N ha^{-1} applied in 2002/03 season
T12	Treatment 1+*T. vogelii* biomass at 30 kg N ha^{-1} applied in 2002/03 season.

by application of *T. vogelii* biomass increased exchangeable Ca values by 3.7 fold, whereas combined application of MPR with *T. vogelii* biomass increased the levels by 4.9 fold. Second application of *T. vogelii* biomass to these two treatments increased exchangeable Ca values by 2.9 and 3.4 fold, respectively. These observations suggest that both MPR application strategies have high potentials in increasing exchangeable Ca values.

The increase in exchangeable Ca in plots treated with *T. vogelii* biomass could be due to increased Ca levels from decomposing biomass with high Ca concentrations (Table 9), as well as Ca released from MPR during its dissolution (Rajan *et al.*, 1996). Increase in exchangeable Ca was also observed in maize fields planted after NF and after *L. leucocephala*, *S. sesban* and *C. cajan* fallows by Onim *et al.* (1990).

The results obtained reveal that incorporation of *T. vogelii* biomass into the soil could significantly improve soil pH and exchangeable Ca. These soil parameters could further be increased by application of *T. vogelii* biomass to soils previously amended with MPR, than combined *T. vogelii* biomass with MPR at the same time. Natural fallow biomass has the potential of increasing exchangeable Ca, though at relatively lower level than to *T. vogelii* fallow biomass.

4.4 Maize Responses to *T. vogelii* Biomass and MPR Applications

The responses of maize to *T. vogelii* biomass and MPR applications were assessed both in glasshouse and in field experiments. Under glasshouse conditions, an assessment was done on maize response to *T. vogelii* leaves and MPR application on a strongly acid P deficient Ferralsol. Under field conditions, maize responses to *T. vogelii* biomass combined with MPR in the first and second post-fallow were evaluated.

4.4.1 Maize response to *T. vogelii* leaves and MPR application on a strongly acid P deficient Ferralsol

The objective of this glasshouse study was to assess under controlled conditions, the response of maize to applications of *T. vogelii* leaves and MPR on a strongly acid (pH 5.0) P deficient Ferralsol.

4.4.1.1 Maize DM yield

Maize DM yields of 42-day old maize plants as influenced by applications of *T. vogelii* leaves and MPR are given in Table 28. The DM yields were significantly increased by applications of TSP+SA, MPR alone or combined with *T. vogelii* leaves, or SA. Application of MPR+SA gave the highest DM yields but was comparable to the yields from TSP+SA and MPR+*T. vogelii* treatments. Application of *T. vogelii* leaves alone depressed DM yields by 13.6% compared to the control. Relative to the control, DM yields were increased by 266 and 309% by combined application of MPR and *T. vogelii* leaves and MPR and SA, respectively. The RAE of MPR was increased from 56% when applied alone to 103 and 119% when it was combined with *T. vogelii* leaves and S/A, respectively. The non significant increase in maize DM yields in soils treated with *T. vogelii* leaves alone was due to N deficiency in maize shoots, which was caused by initial fast N release that did not synchronize with N demands of maize plants. The fineness of ground *T. vogelii* leaves (0.5 mm mesh) used as N source might have released higher N levels initially than that released by ungrounded leaves (Fig. 9). Such high N released by finely ground *T. vogelii* leaves was not taken up by young maize plants with small root systems. Significant responses of maize to MPR applications and to other reactive PRs have been reported by Mnkeni *et al.* (1992), Mutuo *et al.* (1999) and Zahara and Bah, (1997).

Table 28 Influence of combined application of *T. vogelii* leaves and MPR on maize DM yield, shoot N and P concentrations and uptake

Treatments	Maize DM yield ($g\ pot^{-1}$)	MPR - [3]RAE (%)	Shoot N and P concentrations (%)		Shoot N and P uptake ($mg\ pot^{-1}$)	
			N	P	N	P
Control	5.72c	-	0.66d	0.37c	38.8c	21.2d
T. vogelii[1]	4.94c	-	0.82c	0.32d	40.5c	15.8e
MPR[2] + *T. vogelii*[1]	20.94a	102.7	0.94b	0.42b	196.8c	87.9b
MPR[2]	13.98b	55.8	0.46e	0.41b	64.3d	57.3c
MPR[2] + SA[1]	23.42a	119.4	0.95b	0.43b	222.5a	100.7a
TSP[2] +SA[1]	20.54a	100	1.06a	0.47a	217.7b	96.5a

Means bearing the same letter within a column are similar using DMRT at $P \leq 0.05$.
[1]N rate as used from either *T. vogelii* biomass or S/A used was 160 mg N kg^{-1}
[2]P rate used from either MPR or TSP was 160 mg P kg^{-1}
[3]RAE = 100 * Yield increase with MPR relative to control/Yield increase with TSP relative to control

4.4.1.2 Shoot N concentration and uptake

Shoot N concentrations and uptake of 42-day old maize plants as affected by applications of MPR and *T. vogelii* leaves are given in Table 28. Shoot N concentration was significantly increased in all the treatments except in pots treated with MPR alone. Combined application of MPR with either *T. vogelii* biomass or S/A led to similar shoot N concentrations. Application of *T. vogelii* biomass alone resulted in significantly lower tissue N concentrations than the application of MPR+S/A and MPR+ *T. vogelii* biomass. Low shoot N concentrations in soils treated with *T. vogelii* leaves could be attributed to lack of synchrony between N released from the biomass and N demands of maize plants.

In the incubation study, unground *T. vogelii* biomass released 48% of its N in the first 2 weeks, when the N demand of maize was low. Between the second and fourth week the N released was only 10% when N demands for maize was high (Fig. 9). Adequate supply of other essential macro-nutrients is necessary for increased N uptake. Mengel and Kirkby (1982) reported that maximum effect of N can only be expected, if the supply of other plant nutrients is adequate.

However, the shoot N concentrations observed in this experiment are below the adequate range of 3.5-5% reported by Reuter and Robinson (1986) for maize plants at 30-45 days after emergence, suggesting that the plants were all deficient in N, regardless of N sources. The data obtained suggest that the amount of N applied (160 mg N kg^{-1}) was insufficient for optimum maize performance.

Shoot N uptake was significantly increased by combined application of MPR with *T. vogelii* leaves, MPR+S/A and TSP+S/A, but not by *T. vogelii* leaves alone. Shoot N uptake in soils where MPR was combined with *T. vogelii* leaves was significantly lower than that in soils treated with MPR+S/A, indicating that *T. vogelii* leaf biomass was relatively inferior to S/A in supplying N. The N uptake in the control and in soils treated with *T. vogelii* biomass was similar, indicating that N released by the biomass was not efficiently taken up by maize plants.

4.4.1.3 Shoot P concentration and uptake

The effects of applying soil with MPR and *T. vogelii* biomass on shoot P concentration and uptake are presented in Table 28. Shoot P concentration was significantly increased in all the treatments, except in pots treated with only *T. vogelii* biomass which significantly decreased it. As expected the highest and significant shoot P concentrations were observed in pots treated with TSP+S/A. Decreased shoot P concentration in pots treated with *T. vogelii* biomass alone could be caused by low P concentration in *T. vogelii* biomass, which led to wider C:P ratio (Table 9). Low P concentration of less than 0.24% (Palm *et al.*, 1999) and wide C:P ratios greater than 130 (Singh and Jones, 1976) cause P immobilization at least on a short term. The shoot P concentrations were similar in soils applied with MPR alone or combined with either S/A or *T. vogelii* biomass, reflecting the lower P contribution of *T. vogelii* biomass of 8.9 mg P kg^{-1} as compared to 160 mg P kg^{-1} from MPR. The shoot P concentrations in the control and in soils treated with *T. vogelii* biomass were below the adequate range of 0.4-0.8% for maize plants at 30-45 days after emergence (Reuter and Robinson, 1986). The shoot P concentrations in the remaining treatments were in the adequate range.

As expected shoot P uptake was significantly increased by application of TSP+S/A, MPR alone, combined with either *T. vogelii* biomass or S/A, but not by *T. vogelii* biomass application. The shoot P uptake in soils treated with MPR alone was significantly lower than that of MPR combined with *T. vogelii* biomass, suggesting that P uptake from MPR was enhanced by N uptake from ground *T. vogelii* biomass. Mengel and Kirkby (1982) reported that maximum effect of one macronutrient can only be expected, if the supply of other plant nutrients is adequate. This is evidenced by significantly lower shoot P uptake in MPR treated pots than that of MPR+S/A or TSP+S/A treated plots. Shoot P uptake in pots treated with MPR + *T. vogelii* biomass was significantly lower than that of MPR+S/A or TSP+S/A applications. Low shoot P uptake in soils treated with MPR + ground *T. vogelii* biomass compared to that of MPR+S/A or TSP+S/A applications could be due to slight depression of Pi-P (Fig. 11).

4.4.1.4 Relationship between maize DM yields and shoot N and P concentrations

Simple correlation analysis was used to establish the association between DM yields and shoot N and P concentrations. Table 29 presents correlations between DM yields and shoot N and P concentrations. Maize DM production was significantly correlated ($P \leq 0.01$) with shoot P concentrations ($r = 0.875$). Adequate N and P supplies are therefore necessary for optimizing DM yields in strongly acid P deficient Ferralsol.

Table 29. Correlation between DM yields and shoot N and P concentrations

Parameters correlated	Correlation coefficient (r) (df = 5)	Significance
DM yield *vs* shoot N concentration	0.559	Ns
DM yield *vs* shoot P concentration	0.875	**

** significant at 1% level

ns non significant

4.4.2 Response of first post-fallow maize to *T. vogelii* biomass combined with MPR

The first post fallow maize crop was planted after uprooting the 22-month old fallow, and applying different treatments to the experimental plots (Table 5). The data collected include concentrations of N and P in the earleaf collected at tasselling and maize grain yield at harvesting.

4.4.2.1 Earleaf N concentrations

Nitrogen concentrations values of earleaf samples of maize plants are given in Fig. 18. The earleaf N concentrations were significantly increased by all fertilizer treatments. Except for the natural fallow plots, all other treatments had similar earleaf N concentrations, which were within the critical range of 2.7 to 2.9% (Reuter and Robinson, 1986). The earleaf N concentration in the NF plots was in the deficient zone, indicating that a two year old NF cannot accumulate sufficient N for maize production in acid P deficient Ferralsols of Eastern Tanzania. This was due to significantly lower total inorganic-N than that observed in the *T. vogelii* fallow in the 0-20cm depth after a fallow period of 22 months (Fig. 13). Also it was caused by lower N concentration in the NF biomass than that in the *T. vogelii* fallow biomass (Appendix 3). On the other hand, medium term *T. vogelii* fallow (12-24 months) provided sufficient earleaf N concentration regardless of soil P status. This was attributed to improved mineral N concentration in the 0-20 cm depth from the beginning of the experiment (Fig. 13) and N contributed by high quality *T. vogelii* fallow biomass (Appendix 3).

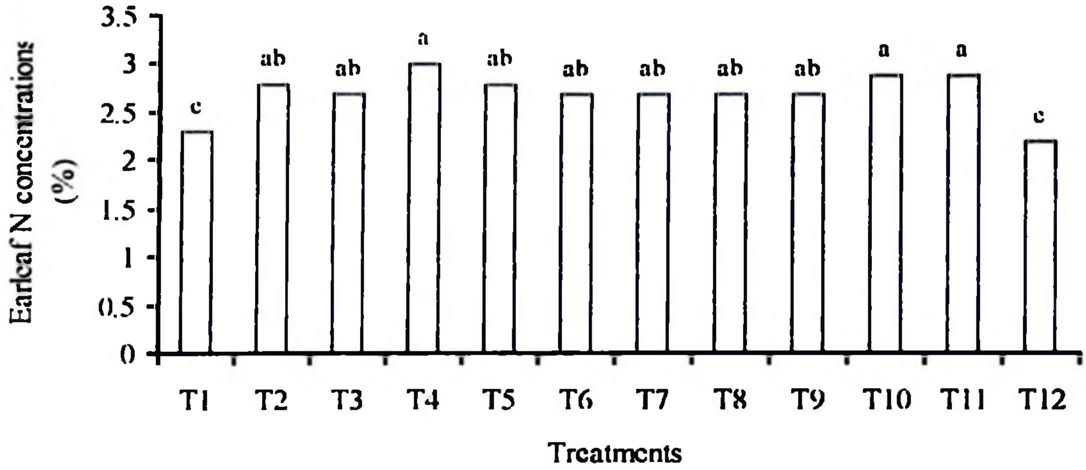


Figure 18. Influence of MPR and fallow biomass applications on earleaf N concentration in maize during 2001/02 season

Legend:

T1	Natural fallow biomass applied at maize planting (2001/02)
T2	S/A (80 kg N ha^{-1}) applied at maize planting (2001/02, 2002/03)
T3	TSP (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T4	MPR (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T5	*T. vogelii* biomass (80 kg N ha^{-1}) applied at maize planting (2001/02)
T6	*T. vogelii* biomass (80 kg N ha^{-1})+MPR applied at *T. vogelii* fallow establishment (1999/00)
T7	*T. vogelii* biomass+combined with MPR at maize planting (2001/02)
T8	Treatment 5+*T. vogelii* relay after maize planting (2001/02)
T9	Treatment 6+*T. vogelii* relay after maize planting (2001/02)
T10	Treatment 7+*T. vogelii* relay after maize planting (2001/02)
T11	Treatment 4+*T. vogelii* relay after maize planting (2001/02)
T12	Treatment 1+*T. vogelii* relay after maize planting (2001/02)

4.4.2.2 Earleaf P concentrations

With regard to earleaf P concentrations, the trend was similar to that of earleaf N concentrations with significantly lower P levels in plots treated with S/A than in the other treatments (Fig. 19). With exception of control plots, the remaining treatments had earleaf P concentrations greater than the critical concentration of 0.25% (Reuter and Robinson, 1986). The results further indicated that application of *T. vogelii* biomass alone improved earleaf P to levels similar to those obtained in TSP or MPR treatments.

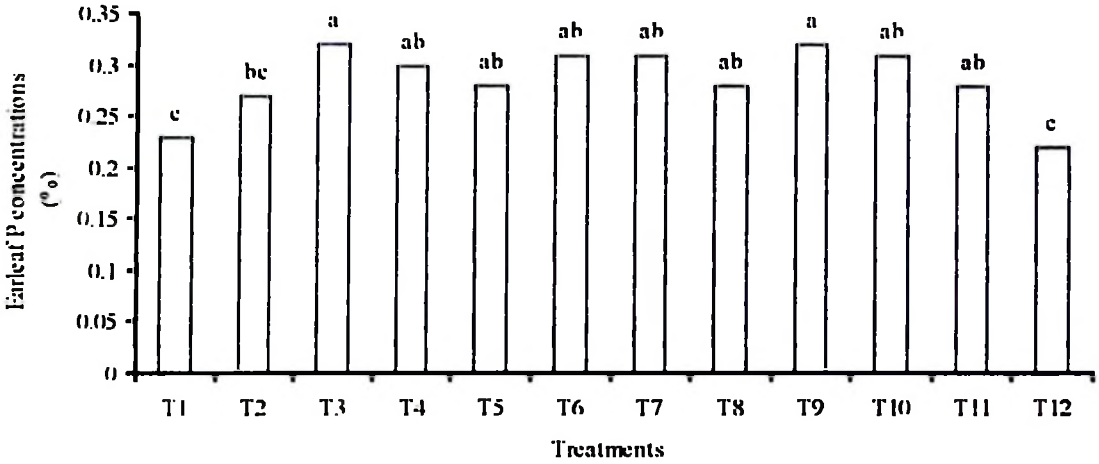


Figure 19. Influence of MPR and fallow biomass applications on earleaf P concentrations in maize during 2001/02 season.

Legend:

T1	Natural fallow biomass applied at maize planting (2001/02)
T2	S/A (80 kg N ha^{-1}) applied at maize planting (2001/02, 2002/03)
T3	TSP (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T4	MPR (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T5	*T. vogelii* biomass (80 kg N ha^{-1}) applied at maize planting (2001/02)
T6	*T. vogelii* biomass (80 kg N ha^{-1})+MPR applied at *T. vogelii* fallow establishment (1999/00)
T7	*T. vogelii* biomass+combined with MPR at maize planting (2001/02)
T8	Treatment 5+*T. vogelii* relay after maize planting (2001/02)
T9	Treatment 6+*T. vogelii* relay after maize planting (2001/02)
T10	Treatment 7+*T. vogelii* relay after maize planting (2001/02)
T11	Treatment 4+*T. vogelii* relay after maize planting (2001/02)
T12	Treatment 1+*T. vogelii* relay after maize planting (2001/02)

The strategies of MPR application had no effect on earleaf P concentrations. The earleaf P concentrations in plots treated with the biomass in the previous year and the received fresh *T. vogelii* biomass application in the second year were the same. However, application of 30 kg N ha^{-1} as *T. vogelii* applied only in the second year and control plot gave similar earleaf P.

4.4.2.3 Relationship between N and P concentrations in soils and in earleaf

Simple correlation analysis was done to establish the relationship between N and P concentrations in soils and N and P concentrations in earleaves of maize plants. Table 30 gives correlations between total inorganic-N and Pi-P concentrations in soils and earleaf N and P concentrations at tasselling. The total inorganic-N values were significantly correlated with earleaf N concentrations (r = 0.681). The earleaf P concentrations were also significantly correlated with Pi-P (r = 0.769). Significant correlations at tasselling between earleaf N *vs* total inorganic-N and earleaf P *vs* Pi-P suggest that adequate N and P supplies are necessary for optimising earleaf N and P in strongly acid P deficient Ferralsol.

Table 30. Correlation between earleaf N and P concentrations and total inorganic-N and Pi-P in soils during 2001/02 season

Parameters correlated	Correlation coefficient (r) (df = 11)	Significance
Earleaf N *vs* total inorganic-N at tasselling	0.681	*
Earleaf P *vs* soil Pi-P at tasselling	0.769	**

** significant at 1%
* significant at 5%

4.4.2.4 Maize grain yield

The first post fallow maize grain yields as influenced by application of MPR, and biomass from natural or *T. vogelii* fallows are given in Fig. 20 and Appendix 18. Application of different fertilizer materials significantly increased maize grain yield. The highest maize grain yield was obtained from treatments in which MPR was applied at *T. vogelii* fallow establishment and latter treated with *T. vogelii* biomass. Application of *T. vogelii* biomass alone or combined with MPR, MPR+S/A and TSP+S/A gave similar but significantly lower maize grain yield than in plots treated with MPR at fallow establishment. Relative to NF plots, maize yield was increased by 147% in plots treated with *T. vogelii* biomass that were amended with MPR at fallow establishment, by 105% in plots where *T. vogelii* biomass was co-applied with MPR, and by 100% in plots applied with *T. vogelii* biomass alone. Compared to application of S/A alone, maize grain yield was significantly increased by 39.6% by application of *T. vogelii* biomass alone.

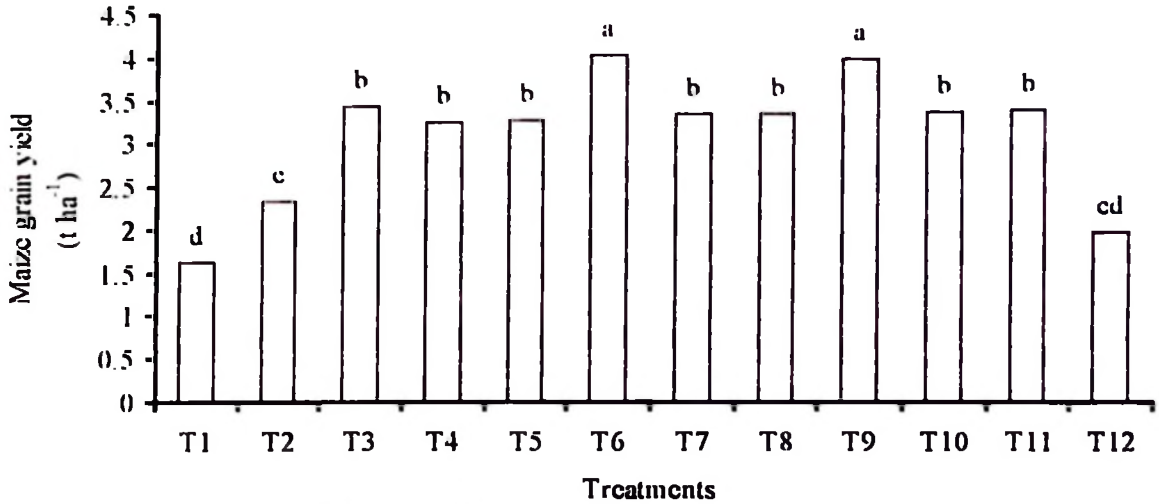


Figure 20. Effects of different MPR and fallow combinations on maize grain yield subsequent to fallow period

Legend:

T1	Natural fallow biomass applied at maize planting (2001/02)
T2	S/A (80 kg N ha^{-1}) applied at maize planting (2001/02, 2002/03)
T3	TSP (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T4	MPR (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T5	*T. vogelii* biomass (80 kg N ha^{-1}) applied at maize planting (2001/02)
T6	*T. vogelii* biomass (80 kg N ha^{-1})+MPR applied at *T. vogelii* fallow establishment (1999/00)
T7	*T. vogelii* biomass+combined with MPR at maize planting (2001/02)
T8	Treatment 5+*T. vogelii* relay after maize planting (2001/02)
T9	Treatment 6+*T. vogelii* relay after maize planting (2001/02)
T10	Treatment 7+*T. vogelii* relay after maize planting (2001/02)
T11	Treatment 4+*T. vogelii* relay after maize planting (2001/02)
T12	Treatment 1+*T. vogelii* relay after maize planting (2001/02)

Improvement in maize grain yield subsequent to *T. vogelii* fallows has been reported by many workers (Drechsel *et al.*, 1996; Gichuru, 1991; Hagedorn *et al.*, 1997; Kwesiga *et al.*, 1999, Mgangamundo, 2000; Murwira *et al.*, 2002; Niang *et al.*, 1996). These workers also found that the duration of *T. vogelii* fallows affected subsequent grain yield. Relative to natural fallow, maize grain yield planted after *T. vogelii* fallows of 2 years was greater than 150% (Gichuru, 1991), while the yield obtained after 1-year fallow ranged between 70 and 100% (Drechsel *et al.*, 1996) and that after 6-months fallow was 33% (Niang *et al*, 1996).

Application of either TSP+S/A, MPR+S/A or *T. vogelii* biomass alone gave similar maize grain yields. This indicates that MPR+S/A application on soils with favourable conditions could be as effective as TSP. Significant increase in maize grain yield by application of *T. vogelii* biomass alone could be caused by consistently higher total inorganic-N during the season (Fig. 14), improved Pi-P (Fig. 15), and increased soil pH and exchangeable Ca (Table 27). Application of S/A alone resulted in significantly lower maize grain yield than treatments which received both N and P, suggesting that S/A alone cannot optimize yield in P deficient Ferralsols.

Relaying *T. vogelii* with maize plants had no effect on maize grain yield, possibly due to young age and lower plant population. At tasselling, the relayed *T. vogelii* plants were 15 days old. At Rubona Rwanda, Drechsel *et al.* (1996) reported that delaying planting date of *T. vogelii* plants by 2-3 weeks reduced competition with maize.

4.4.2.5 Relationship between maize grain yields and total inorganic-N, Pi-P, and earleaf N and P concentrations

Table 31 gives correlations relationships between maize grain yields and total inorganic-N, Pi-P concentrations in soil and earleaf N and P concentrations. Maize grain yield was significantly correlated with total inorganic-N at tasselling (r = 0.63), earleaf N (r = 0.66), earleaf P (r = 0.90) and Pi-P (r = 0.75). The concentrations of earleaf P explained 80% of the variation in grain yield whereas Pi-P concentrations explained 56% of the variation in yield. The earleaf N concentrations on the other hand explained 43% of the variation in grain yield and total inorganic-N explained 40% of the variation in grain yield. These relationships suggest that in acid P deficient Ferralsol, available P was more important than total inorganic-N in improving maize grain yield

Table 31. Correlation relationships between maize grain yield and total inorganic-N, Pi-P and earleaf N and P concentrations during 2001/02 season

Parameter	Correlation coefficient (r) (df = 11)	Significance
Total inorganic-N at planting	0.48	ns
Total inorganic-N at vegetative	0.33	ns
Total inorganic-N at tasselling	0.63	*
Earleaf N	0.66	*
Earleaf P	0.90	**
Pi-P	0.75	**

ns non significant
* significant at 5%
** significant at 1%

4.4.2.6 Relative agronomic effectiveness of different P sources

Since maize grain yield was highly correlated with earleaf P and Pi-P (Table 31), it was therefore important to assess relative agronomic effectiveness of the P sources used in the experiment Relative agronomic effectiveness of different P sources is given in Appendix 18. Application of *T. vogelii* biomass alone led to an incremental maize grain yield of 0.5% compared to addition of MPR+S/A. Combined application of *T. vogelii* biomass and MPR led to 4.9% increase in grain yield relative to MPR+S/A application. Application of MPR at establishment of *T. vogelii* fallow followed by application of *T. vogelii* biomass at maize planting had RAE values of 130% with- and 133.1% without-*T.* vogelii relay. This is equivalent to an increase of about 30% compared to that of standard fertilizer recommendation of TSP+S/A. Under these soil conditions, MPR was 90% as effective as TSP. A similar response pattern of maize to MPR and TSP applications has been reported elsewhere. In acid soils of Western Kenya, Mutuo *et al.* (1999) reported that MPR produced maize yield increases relative to TSP ranging from 80 to > 100%.

These observations indicate that inadequate P levels in these soils severely limits maize yields, and that application of *in situ T. vogelii* biomass alone or with MPR could substantially improve maize grain yield, but is more beneficial when MPR is applied to *T. vogelii* fallow at establishment.

4.4.3 Response of the second post-fallow maize crop

The second post fallow maize crop was planted after uprooting 11-month old relayed *T. vogelii* plants. The data collected include earleaf N and P concentrations at tasselling and maize DM yields.

4.4.3.1 Earleaf N and P concentrations

Table 32 gives earleaf N and P concentrations as influenced by the application of different fertilizers. Earleaf N concentration was significantly increased by all residual and current fertiliser applications. Except for control and plots treated with *T. vogelii* biomass at 30 N ha^{-1}, the earleaf N concentrations of the remaining treatments were similar. However, earleaf N concentrations observed are lower than critical earleaf N concentration of 2.7 to 2.9%, indicating that N uptake by the maize crop was low. Lack of adequate rainfall in 2002/03 season is likely to have affected N uptake by maize plants.

Earleaf P concentration, on the other hand, was not affected by application of the different fertilizers and materials. Generally, earleaf P concentrations were very low and similar regardless of the fertilizer material applied. Non significant difference in earleaf P concentration was probably caused by prolonged dry spells during 2002/03 season. Although Pi-P in 2002/03 season was high (Appendix 15), long dry spells caused poor utilization of available P because the diffusion rate of P was decreased (Mengel and

Kirkby, 1982). In addition, inadequate soil moisture reduces decomposition of organic materials and P release from MPR (Giller and Wilson 1991; Rajan *et al.*, 1986).

4.4.3.2 Dry matter yield

In the 2002/03 season, the maize crop failed due to very low rainfall (Appendix 4), as such only maize DM yield was harvested and is presented in Table 32. Application of MPR at establishment of *T. vogelii* fallow followed by fallow biomass at 2001/02 season (Treatment 6) gave the highest DM yield which was significantly different from all treatments except treatment 7. Application of *T. vogelii* fallow biomass alone or combined with MPR in the 2001/02 season (treatments 5, 7) also increased maize DM yields significantly. The second application of T. vogelii biomass in the 2002/03 season (treatments 8-10) gave significantly lower DM yields than treatments 5,6 and 7. Application of *T. vogelii* fallow biomass at 30 kg N ha^{-1} on plots treated with natural fallow biomass in 2001/02 season (treatment 12) had no effect on maize DM yields. Maize DM yields were slightly increased by MPR+S/A application in the 2001/02 season followed by *T. vogelii* fallow biomass at 30 kg N ha^{-1} (Treatment 11).

Generally, the DM yields obtained from plots that were treated with *T. vogelii* fallow biomass at 80 kg N ha^{-1} in the 2001/02 season (treatments 5-7) were higher than in the remaining treatments. The lower DM yields in plots treated with second dosesof *T. vogelii* biomass in the 2002/03 season were attributed to lower N and P uptake caused by inadequate moisture. At Gairo, Tanzania Mkangwa (2003) observed variations in yields of maize treated with P were associated with low total rainfall and uneven distribution.

Table 32. Second post-fallow maize response to application of fallow biomass, and N and P

Treatment	Leaf N and P concentration (%)		Maize DM yield (t ha^{-1})	RE[1](%)
	N	P		
T1	1.51 c	0.07 a	1.94 h	
T2	1.80 ab	0.07 a	3.06 g	
T3	1.98 a	0.08 a	3.56 fg	100.0
T4	1.82 ab	0.07 a	4.71 de	170.9
T5	1.80 ab	0.06 a	5.38 bc	212.3
T6	1.87 a	0.06 a	6.08 a	255.6
T7	1.77 ab	0.06 a	5.57 ab	224.1
T8	1.93 a	0.05 a	4.68 de	169.1
T9	1.86 a	0.05 a	4.89 cd	182.1
T10	1.82 ab	0.06 a	4.72 de	171.6
T11	1.91 a	0.06 a	4.95 cd	185.8
T12	1.58 bc	0.06 a	2.06 h	7.4

Means bearing the same letter within a column are similar using Duncan's Multiple Range Test at $P \leq 0.05$

Legend:

T1 Natural fallow biomass applied at maize planting (2001/02, 2002/03)
T2 S/A (80 kg N ha^{-1}) applied at maize planting (2001/02, 2002/03)
T3 TSP (80kgPha^{-1})+S/A (80 kg N ha^{-1})applied at maize planting (2001/02)
T4 MPR (80 kg P ha^{-1})+S/A (80 kg N ha^{-1}) applied at maize planting (2001/02)
T5 *T. vogelii* biomass (80 kg N ha^{-1}) applied at maize planting (2001/02)
T6 *T. vogelii* biomass (80 kg N ha^{-1})+MPR applied at *T. vogelii* fallow establishment (1999/00)
T7 *T. vogelii* biomass+combined with MPR at maize planting (2001/02)
T8 Treatment 5+*T. vogelii* biomass applied at 30 kg N ha^{-1} (2002/03)
T9 Treatment 6+*T. vogelii* biomass applied at 30 kg N ha^{-1} (2002/03)
T10 Treatment 7+*T. vogelii* biomass applied at 30 kg N ha^{-1} (2002/03)
T11 Treatment 4+*T. vogelii* biomass applied at 30 kg N ha^{-1} (2002/03)
T12 Treatment 1+*T. vogelii* biomass applied at 30 kg N ha^{-1} (2002/03)
[1]Residual Effectiveness (%) = RE-PR * 100 / RE-TSP

4.4.3.3 Relationship between maize DM yields and N and P concentrations in soils and in earleaf samples

The correlations between maize DM yields and total inorganic-N and Pi-P concentrations and foliar N and P levels during the 2002/03 rainy season are given in Table 33. The DM yield was significantly correlated with Pi-P ($P \leq 0.01$) and earleaf N, but not with concentrations of total inorganic-N. This indicates that the treatments improved Pi-P, which in turn improved DM yields. The earleaf P concentration was non significantly correlated with DM yield of maize. However, the positive effects demonstrated by Pi-P were not reflected in earleaf P because of poor efficiency in utilization of the available P. Thus, the P concentrations in earleaf were similar and in the deficiency range.

Table 33. Correlation between maize DM yields and N and P concentrations in soils and in earleaf during 2002/03 rainy season

Parameter	Correlation coefficient (r) (df = 11)	Significance
Total inorganic-N at vegetative	0.362	ns
Total inorganic-N at tasselling	0.149	ns
Earleaf N	0.647	*
Earleaf P	-0.286	ns
Pi-P	0.690	**

ns: non significant
*: significant at 5%
**: significant at 1%.

Non significant correlations of earleaf P ($r = -0.286$) and total inorganic-N ($r = 0.362$, $r = 0.149$) to maize DM yield could be due to long dry spells (Appendix 4). Severe moisture stress during the season affected N and P uptake, which consequently affected maize DM accumulation. In Uganda, Siriri and Raussen (2002) observed that over 50% of maize grain yield subsequent to *S. sesban*, *Acanthus pubenscens*, *Calliandra calothyrsus*, *Alnus acuminata* and *T. vogelii* fallows was attributed to water availability.

4.4.3.4 Residual effectiveness of different fertilizers in the second post-fallow maize crop

The RE of different fertilizer materials as compared to TSP is given in Table 32. Despite the inadequate rains, application of MPR at establishment of fallows in 1999/00 season followed by addition of *T. vogelii* biomass in 2001/02 season, had the highest RE of 255%. Higher RE values than the control (standard P source) were also observed in plots treated with *T. vogelii* alone or co-applied with MPR in 2001/02. This could be caused by increased P release from MPR with time and P released from organic residues of *T. vogelii* biomass. Addition of fallow biomass in 2002/03 season reduced RE considerably due to reduced P uptake caused by severe moisture stress (Fig 3).

Increased RE of PRs with time has been reported elsewhere by Kamasho *et al.* (1996) and Mokwunye and Bationo (2002). In a glasshouse study, Kamasho *et al.* (1996) reported that the RE of MPR on maize DM yield was increased from 74 in the first to 87% in second maize crop. In Togo, Mokwunye and Bationo (2002) observed that RE of Togo PR on maize grain yield was increased from 91% in the first year to 111% in the second year.

4.5 Implications of combined use of *T. vogelii* fallow and MPR in acid P deficient Ferralsols

The implications of combined use of *T. vogelii* fallow and MPR in the sub-humid climate of the SUA Farm in Eastern Tanzania is based on *T. vogelii* fallow response to prevailing soil and climatic conditions when treated with or without MPR at establishment. In such situations, the implications were based on adaptability, productivity, effects when relayed with maize of *T. vogelii* fallow, and fallow effects on subsequent soil fertility and maize yields.

4.5.1 Adaptability

4.5.1.1 Soil properties

Soil acidity and low available P reduced both quantity and quality of *T. vogelii* biomass. In the short term (3-6 months), strong soil acidity (pH < 5.5) and low Bray-I P (< 10 mg P kg^{-1}) depressed biomass quality and quantity and N_2-fixing capacity of *T. vogelii* seedlings. In the medium duration (14-24 months) fallows, soil acidity and P deficiency significantly reduced biomass, N and P accumulations.

Application of MPR improved total biomass yield, N and P accumulation in both short term and in the 22-month old *T. vogelii* fallows. However, amending strongly acid Ferralsols with MPR alone did not eliminate all soil factors limiting N_2-fixing capacity of *T. vogelii* plants.

4.5.1.2 Prevailing climate

Climate especially, the long dry season reduced survival of *T. vogelii* plants. Late planting close to the beginning of the long dry season reduced the survival of *T. vogelii* plants down to 43% within the first 6 months. Early planting increased survival of young plants. Research in Rwanda and Kenya has revealed that due to slow initial growth of *T. vogelii* plants, a well-distributed rainy season of 4-5 months is required to give adequate growth to withstand the subsequent dry season (Amadalo *et al*., 2003; Drechsel *et al*., 1996) In Eastern Tanzania, such a long and reliable rainy season is experienced only in few locations.

4.5.2 *Tephrosia vogelii* fallow productivity

4.5.2.1 Sole planted *T. vogelii* fallow

(i) Litter and biomass production

Despite low survival of *T. vogelii* plants, application of MPR led to litter production comparable to other sites. The total litter produced was increased by 2.3-fold by MPR application. However, the standing biomass at the end of fallow period was not affected by MPR application.

(ii) Nitrogen and P accumulation

The nutrient accumulation in the *T. vogelii* fallows varied with plant components, P application and seasons. Application of MPR at *T. vogelii* fallow establishment increased N and P accumulations in litter, leaves and stems. The N and P accumulation increased by 2.4 and 3-fold for litter, 1.2 and 1.1-fold for leaves and 1.9 and 3.9-fold for stems, respectively due to MPR application. Litterfall accumulated more nutrients followed by stems. The total N and P accumulated in the stems accounts for 27 and 62.5%, respectively for total N and P accumulated in the fallows amended with MPR at establishment. Variability in nutrient accumulation of *T. vogelii* fallows was also due to seasonal variation, which was low during the dry season and high in the rainy season.

(iii) Pests and disease infection

In the period of 22 months, *Fusarium* wilt and root knot nematodes infected *T. vogelii* plants. The extent of root knot nematodes infection was not established but the survival of *T. vogelii* plants was reduced by 12% by *Fusarium* wilt infection during the 22-month period.

4.5.2.2 Performance of relayed *T. vogelii* plants

(i) Survival and biomass accumulation

The survival of early planted relayed *T. vogelii* plants at 11-months was 26% higher than that of sole, late planted *T. vogelii* in 1999/00 season. Due to very slow initial growth of *T. vogelii* plants, the biomass and consequently N accumulated in the 11-month old relayed plants was very low. This implies that *T. vogelii* plants require a longer period in the field to accumulate enough biomass that can supply adequate N levels.

(ii) Effects of relayed *T. vogelii* plants on maize

The relayed *T. vogelii* plants had no effect on maize yield. Maize grain yield in the relayed *T. vogelii* plants and in pure maize stand was similar. However, because the end of rainy season in the sub-humid climate is uncertain, relaying of *T. vogelii* may be risky and could lead to total failure of *T. vogelii* fallows.

4.5.3 Effects of fallows on soil fertility regeneration

4.5.3.1 Nitrogen release from *T. vogelii* leaves and N and P availability in soils

An incubation study using litterbags indicated that during decomposition of *T. vogelii* leaves, mass loss and N release patterns have three phases. Rapid decomposition rate occurred during the first 14 days, followed by a slower rate of decomposition (14-56 days) and an intermediate rate of decomposition thereafter up to 84 days. Application of MPR increased the rate of decomposition of *T. vogelii* leaves only in the first 4 weeks, but had no effect on N release. During the rapid decomposition phase, *T. vogelii* biomass released 48% of its N, and at the end of 84 days of incubation total N released was 69%. However, at 84 days of incubation total N concentration in the residues was 2.4%, indicating that N could continue to be available thereafter.

In the incubation study, combined application of MPR with ground *T. vogelii* leaves depressed available P. In the glasshouse experiment application of either MPR+*T. vogelii* or MPR followed by maize cropping resulted in similar Pi-P values. Under field conditions, *T. vogelii* fallows increased available P, but the increases were low and the amounts were likely to be inadequate for the subsequent crop. Subsequent to fallows, available P was increased by *T. vogelii* fallows biomass applied alone or in combination with MPR. Application of MPR at fallow establishment, led to higher available P level.

4.5.3.2 Total inorganic-N

Total inorganic-N concentrations were improved in *T. vogelii* fallow that were treated with MPR at fallow establishment both in the dry season and at the onset of the first rains. At the onset of the first rains, the total inorganic-N was distributed almost equally in the top and subsoil of the fallows tested. Application of MPR at fallow establishment led to higher total inorganic-N concentrations.

In subsequent seasons, total inorganic-N concentrations were higher at the beginning but gradually declined as rains progressed. Throughout the season, application of *T. vogelii* fallow biomass alone led to significantly higher total inorganic-N concentrations than in combination with MPR.

4.5.3.3 Soil pH and exchangeable Ca

Application of *T. vogelii* biomass at 80 kg N ha^{-1} also contributed 4 kg P and 97 kg Ca ha^{-1}. Application of MPR at establishment of *T. vogelii* fallows, followed by fallow biomass application resulted in higher soil pH than *T. vogelii* and natural fallow biomass. Application of natural and *T. vogelii* fallow biomass increased exchangeable Ca.

Generally, soil fertility regeneration particularly of N and P in the fallows increased irrespective of fallow type, with higher regeneration in *T. vogelii* fallows amended with MPR than in the other fallows. Application of fallow biomass in subsequent cropping seasons also led to significant improvements in total inorganic-N, available P, soil pH and exchangeable Ca. Increased improvements in total inorganic-N, available P, soil pH and exchangeable Ca imply that a medium term *T. vogelii* fallows has potential of improving soil fertility.

4.5.4 Maize responses to *T. vogelii* biomass and MPR application

Under glasshouse conditions, application of MPR alone or combined with *T. vogelii* biomass significantly increased tissue N and P uptake and maize DM yields. Under field conditions, earleaf N and P concentrations and maize yields varied with the rainfall.

In the high rainfall year (2001/02), earleaf N and P concentrations were significantly increased to sufficient levels by application of *T. vogelii* fallow biomass alone or combined with MPR. Both total inorganic-N and available P were highly correlated with earleaf N and P concentrations. Maize grain yield was significantly increased by *T. vogelii* fallow biomass applied alone or with MPR at maize planting. The higher maize grain yield was obtained in plots treated with MPR at establishment of *T. vogelii* fallow, combined with *T. vogelii* biomass at maize planting, which also led to higher relative agronomic effectiveness of 130%.

In the low rainfall year (2002/03), earleaf N concentrations were increased due to residual effects of *T. vogelii* biomass alone or combined with MPR, and freshly applied *T. vogelii* biomass. However, earleaf N concentrations were below the N critical concentration. On the other hand, earleaf P concentrations were not affected by the treatments and all values were in the deficiency range. Both application of MPR at establishment of *T. vogelii* fallow followed by application of fallow biomass, and combined application of MPR + *T. vogelii* biomass at maize planting in the first post-fallow cropping led to the higher DM yields. However, fresh applications of *T. vogelii* biomass decreased maize DM yields.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

On the basis of the data generated in this study, the following conclusions were made:

(a) Strong soil acidity (pH < 5.5) and low Bray-I P levels of < 3 mg P kg^{-1} adversely reduced N_2-fixation of *T. vogelii* plants, and quantity and quality of its biomass. In such strongly acid and P deficient Ferralsols, P was more important than Ca for improvement of quantity and quality of *T. vogelii* biomass.

(b) Medium term fallow period (14-24 months) improved biomass and nutrient accumulation, while nutrients accumulated by relayed *T. vogelii* fallows grown for 11-months were inadequate for a subsequent crop. Litterfall was the major source of nutrients from the medium term *T. vogelii* fallows.

(c) Application of MPR at *T. vogelii* fallow establishment increased total inorganic-N and Pi-P in the fallows.

(d) Minjingu PR application increased the rate of *T. vogelii* biomass decomposition only in the first four weeks, but N release from the biomass was not affected.

(e) Combined application of MPR with *T. vogelii* biomass depressed Pi-P while application of MPR alone increased it.

(f) Application of *T. vogelii* biomass improved total inorganic-N concentrations to a greater extent than natural fallow biomass throughout the rainy season. It also improved Pi-P, and earleaf N and P concentrations to sufficiency levels.

(g) Application of *T. vogelii* fallow biomass improved exchangeable Ca to a greater extent than NF biomass, whereas application of MPR at *T. vogelii* fallow establishment had a greater effect on soil pH than combined application of *T. vogelii* biomass and MPR.

(h) Application of MPR at *T. vogelii* fallow establishment followed by incorporation of fallow biomass produced higher maize grain yield to a greater extent than combined application of MPR and *T. vogelii* fallow biomass. Application of *T. vogelii* fallow biomass alone resulted in higher maize grain yield than NF biomass.

5.2 RECOMMENDATIONS

Based on the findings generated from in this study, the following recommendations ere made:

(a) The use of *T. vogelii* fallows in improving soil fertility and subsequent maize yield is promising even under harsh conditions of drought used in this experiment. The technology can be taken to the farmers for further testing in soils with favourable pH (pH 6-7.5) and a shorter dry season of less than 4 months long.

(b) Under the sub-humid climate used in this study, litterfall appears to be a major source of nutrients in medium term (14-24 months) fallows. Under these conditions, very little is known on management and decomposition pattern of the litter produced. Therefore, research is required on these issues, so that the litter accumulated can be efficiently utilized in subsequent seasons.

(c) Erratic rains received in the sub-humid climates of Morogoro poses serious problems in establishment and subsequent growth of *T. vogelii* plants. It is therefore important to conduct further research that will establish appropriate planting time so that undesirable effects of the long dry season are minimized.

(d) In areas with adequate rains, strongly acid and P deficient soils, MPR can be directly applied at establishment of *T. vogelii* fallow and become an indirect pathway of improving P availability to the subsequent maize crop.

(e) The strategy of MPR application at fallow establishment needs to be further tested to include other high P fixing soils, with more wider gap of acidity, available P and rainfall conditions, so that conclusions obtained could be used more widely.

(f) The strategy of MPR application at fallow establishment also requires further evaluation using other N_2-fixing leguminous shrubs like *T. candida*, *C. ochroleuca*, and *C. cajan*, so that a farmer can select from a wide range of fallow species.

(g) Since *Fusarium* wilt infection reduces survival of *T. vogelii* plants, further research is needed to screen other N_2-fixing leguminous plants against this disease.

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APPENDICES

Appendix 1. Profile description of the trial site

Profile number: BP-1.
Region: MOROGORO; District: MOROGORO URBAN; Map sheet no.: 183/3
Coordinates: 06°50'24.5"S 37°39'12.4"E.
Location: Agroforestry experimental site (about 500-m southwest of SUA farm access road to Iringa road). Elevation: 540 m asl. Parent material: Colluvium derived from Uluguru Mountains. Landform: Peneplain-Backslopes; gently undulating; Slope: 1.5-2 %, straight, >200 m, middle slope. Surface characteristics: Erosion: moderate sheet and rill erosion. Deposition: colluvial deposits. Surface stoniness: none. Flooding: none. Natural drainage class: well drained. Natural vegetation: Grassland / shrubs mostly *Acacia mangium, Lantana camara, Tephrosia spp., Gliricidia sepium, Leucaena leucecophala, Senna obtusifolia* and *Solanum incanum*, and grasses dominant species include *Andropogon gayanus, Launaea cornuta, Panicum maximum, Oxygonum sinuatum* and *Commelina benghalensis*. Land use: Cultivation of maize and tree planting. Described by C.Z. Mkangwa and E.P. Kileo on 12/04/2000.

Soil are very deep, well drained dark red to red clays with very thick dusky red clay topsoils. Few crotovinas and black ants were observed at Ap, AB and Bt1 horizons.

Ap 0 - 20/30 cm: dusky red (7.5R3/3) moist; clay; friable moist, sticky and plastic wet; moderate to strong fine and medium subangular blocky; many fine and medium pores; many fine and very fine roots; clear wavy boundary to

AB 20/30 - 39/53 cm: dark red (7.5R3/6) moist; clay; very friable moist, slightly sticky and slightly plastic wet; strong fine and medium subangular blocky; many fine and very fine pores; common thin clay cutans; many fine and very fine roots; diffuse wavy boundary to

Bt1 39/53 - 90/93 cm: dark red (7.5R3/8) moist; clay; friable moist, slightly sticky and slightly plastic wet; moderate to strong fine and medium subangular blocky; many very fine pores; common thin clay cutans; very few fine roots; diffuse wavy boundary to

Bt2 90/93 - 180+ cm: red (7.5R4/8) moist; clay; friable moist, slightly sticky and slightly plastic wet; moderate to strong fine and medium subangular blocky; many very fine pores; common thin clay cutans; very few fine roots.
SOIL CLASSIFICATION: WRB (FAO 1998): Hyperdystri-Umbric Ferralsol
USDA-Soil Taxonomy (Soil Survey Staff, 1999): Typic Haplustox

Appendix 2. Analytical data for profile BP-1

Horizon	Ap	AB	Bt1	Bt2
Depth (cm)	0-20/30	20/30-39/53	39/53-90/93	90/93-180+
Clay (%)	57.2	63.2	63.2	61.2
Silt (%)	10.8	8.8	10.8	16.8
Sand (%)	32	28	26	22
Texture class	C	C	C	C
Bulk density (g cm^{3})	1.3	1.3	1.3	1.4
AWC (mm m^{-1})	nd	nd	nd	31.4
pH-H_2O (1:2.5)	4.8	4.7	5.4	5.7
pH-KCl (1:2.5)	4.2	3.7	4.0	3.4
ESP (%)	1.72	1.20	1.37	2.82
Organic C (%)	1.02	0.73	0.43	0.26
Total N (%)	0.12	0.04	0.04	0.04
C/N	8.5	18.25	10.75	6.5
Available P Bray-I (mg kg^{-1})	1.43	0.97	0.23	0.17
Available Pi-P (mg kg^{-1})	1.2	0.72	0.32	0.26
CEC NH_4OAc (cmol(+) kg^{-1})	9.3	8.3	7.3	8.5
Exch. Ca (cmol(+) kg^{-1})	2.44	1.64	0.70	0.63
Exch. Mg (cmol(+) kg^{-1})	1.62	0.98	1.88	0.69
Exch. K (cmol(+) kg^{-1})	0.27	0.13	0.10	0.09
Exch. Na (cmol(+) kg^{-1})	0.16	0.10	0.17	0.24
TEB (cmol(+) kg^{-1})	4.49	2.85	2.82	1.65
Base saturation (%)	48.28	34.34	38.63	19.41
CEC clay (cmol(+) kg^{-1})	10.11	9.15	9.20	12.42

nd= not determined

Appendix 3. Nutrient contents of *T. vogelii* and natural fallow biomass

	Nutrients concentration (%)			Nutrient applied (kg ha^{-1})		
Fallow type	N	P	Ca	N	P	Ca
NF biomass	0.8	0.08	1.1	25.6	2.4	34
T. vogelii litter	1.5	0.1	2.2	60	3.2	88
T. vogelii leaves	3.3	0.13	1.5	20	0.9	9.1

Appendix 4. Rainfall distribution in 2001/02 and 2002/03 long rains

Date	Rainfall amount received (mm)									
	January		February		March		April		May	
	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003
1	0	38	0	0	0	0	0	0	0	0
2	0	0	0	0	2	0	8	0	0	0
3	3	26	0	0	22	0	0	0	0	0
4	0	0	0	0	9	0	26	0	0	0
5	0	0	0	0	0	0	7	0	0	4
6	0	0	0	0	0	0	5	0	0	0
7	0	0	0	0	0	0	0	29	0	4[3]
8	0	0	0	0	8	0	3	0	0	0
9	0	0	0	0	0	0	11	0	0	0
10	0	25	0	0	0	0	7	0	0	0
11	8	0	0	0	22	0	15	0	0	0
12	0	0	0	0	26	0	0	5	0	0
13	0	0	0	24	0	25	72	0	0	0
14	0	0	12	0	2	25[1]	0	0	0	0
15	0	0	36	0	38	0	26	0	0	0
16	1	0	0	0	0	0	3	29	0	0
17	0	0	30	0	0	0	2	3	0	0
18	0	0	0	0	0	0	3	0	6	0
19	0	0	0	0	8	0	44	0	0	0
20	0	0	0	0	0	2	4	0	0	0
21	0	0	0	0	0	0	7	0	7	0
22	5	0	0	0	0	0	6	0	0	19
23	3	0	0	0	0	0	0	0	0	0
24	0	0	0	0	5	0	0	0	0	0
25	0	0	0	0	0	3	7	0	0	0
26	7	0	0	0	0	86	4	0	0	8
27	0	0	0	0	0	0[2]	3	0	0	0
28	1	0	12	0	10	0	0	0	0	0
29	0	0	0	0	0	8	3	0	0	0
30	0	0			0	0	30	0	0	0
31	0	0			0	8			0	16

Legend

25[1] Date of maize planting

0[2] First sampling date for total inorganic-N determination

4[3] Second sampling date for total inorganic-N determination

Appendix 5. Effect of MPR application on *T. vogelii* litterfall dry weight, N and P concentrations and accumulations in the 12 to 22 months

T. vogelii fallow age (months)	Seasons	Litter DM (t ha^{-1})	Litter N and P concentrations (%)		Total litter N and P accumulations (kg ha^{-1})	
			N	P	N	P
12	Wet	0.860abc	1.43a	0.061a	12.3ba	0.55a
14	Dry	0.538b	1.44a	0.049b	8.0b	0.27a
16	Dry	1.137a	1.45a	0.061a	17.1a	0.75a
18	Dry	0.917ab	1.40a	0.062a	13.7ba	0.59a
22	Wet	0.610c	1.20b	0.041c	7.4b	0.25a
CV (%)		44.55	8.11	26.35	6.6	12.8

Means bearing the same letter within a column and fallow age are similar by DMRT at $P \leq 0.05$

Appendix 6. Influence of fallow age and seasons on leaf N and P concentrations of 6, 12, 18 and 22 month old *T. vogelii* plants

Fallow age / season (months)	Leaf N and P concentrations (%)	
	N	P
6 / Dry	2.8a	0.11c
12 / Wet	2.9a	0.12b
18 / Dry	2.4b	0.10d
22 / Wet	3.2a	0.13a
CV(%)	6.5	12.4

Means bearing the same letter within a column are similar by DMRT at $P \leq 0.05$

Appendix 7. Influence of MPR application on proportional of initial weight of *T. vogelii* leaves and N at each retrieval period

Retrieval period (weeks)	P applied (kg ha^{-1})			
	0	80	0	80
	Proportion of *T. vogelii* leaves remaining		Proportion of total N remaining	
0	1.0a	1.0a	1.0a	1.0a
2	0.708a	0.672b	0.53a	0.51a
4	0.572a	0.520b	0.44a	0.46a
8	0.502a	0.491a	0.38a	0.37a
12	0.284a	0.354a	0.25a	0.20a

Means bearing the same letter in the same retrieval period and retrieved material are similar using t - test at $P \leq 0.05$

Appendix 8. Nitrogen concentrations in *T. vogelii* residues

Retrieval period (weeks)	P applied (kg ha^{-1})	
	0	80
	N concentration in retrieved residues (%)	
0	3.4 a	3.4 a
2	2.85 a	2.69 a
4	2.63 a	2.51 a
8	2.57 a	2.47 a
12	2.38 a	2.37 a

Means bearing the same letter in the same retrieval period and retrieved material are similar using t - test at $P \leq 0.05$

Appendix 9. Influence of co-application of MPR and *T. vogelii* biomass on Pi-P

Treatments	Sampling period (days)					
	1	7	14	28	56	84
	------------*Pi* - P (mg P kg^{-1})------------					
Soil alone	1.86b	1.12b	1.26b	1.87c	1.91c	1.89c
Soil + *T. vogelii* biomass	1.71b	1.45b	1.49b	1.45c	1.60c	2.45c
Soil + MPR	10.78a	11.5a	10.97a	11.57a	11.57a	22.65a
Soil + MPR + *T. vogelii* biomass	9.27a	9.44a	9.09a	10.29b	10.28b	18.55b
CV (%)	30.64	32.26	22.45	14.35	7.40	19.60

Means bearing the same letter within a column are similar by DMRT at $P \leq 0.05$

Appendix 10. Effect of co-applying *T. vogelii* biomass and MPR on Pi-P at maize harvesting

Treatments	Pi-P (mg P kg^{-1})
Control	1.67c
T. vogelii^{1}	4.3bc
MPR^{2} + *T. vogelii*^{1}	9.14a
MPR^{2}	8.59a
MPR^{2} + SA^{1}	10.02a
TSP^{2} +SA^{1}	6.78ab
CV (%)	27

Means bearing the same letter are similar by DMRT at $P \leq 0.05$

SA^{1} rate of N as *T. vogelii* biomass or S/A used is 160 mg N kg^{-1}

MPR^{2} rate of P as MPR or TSP used is 160 mg P kg^{-1}

Appendix 11. Total inorganic-N as influenced by MPR application, fallow type and season

Treatment	Depth (cm)	Total inorganic-N (mg kg^{-1}) 15 August 2001 (Dry season)	19 February 2002 (Onset of the rains)
NF	0-20	21.6 bc	29.8 b
NF	20-40	7.1 d	30.8 b
T. vogelii	0-20	28.4 b	43.8 ab
T. vogelii	20-40	8.7 d	40.2 ab
T. vogelii + MPR	0-20	39.1 a	54.9 ab
T. vogelii + MPR	20-40	13.4 cd	59.7 a

Means bearing the same letter within a column are similar by DMRT at $P \leq 0.05$

Appendix 12. Influence of applying MPR to *T. vogelii* fallows on seasonal mineral-N dynamics in the fallows

Fallow type	Soil depth (cm)	15 August 2001 (Dry season)		19 February 2002 (Onset of the rains)	
		NH_4-N	NO_3-N	NH_4-N	NO_3-N
		(mg kg^{-1})			
Natural fallow	0-20	5.0 ab	16.6 c	6.2 c	23.6 bc
Natural fallow	20-40	1.6 c	5.5 d	9.1 b	21.7 c
T. vogelii alone	0-20	4.0 abc	24.4 b	7.6 bc	36.2 abc
T. vogelii alone	20-40	2.6 bc	6.1 d	9.8 b	30.4 abc
T. vogelii+MPR	0-20	6.8 a	33.1 a	12.8 a	42.1 ab
T. vogelii+MPR	20-40	3.7 bc	9.7 d	13.4 a	46.3 a
CV (%)		34.79	18.3	11.04	29.8

Means bearing the same letter within a column are similar by DMRT at $P \leq 0.05$

Appendix 13. Effect of fallow biomass and MPR applications on total inorganic-N in 2001/02 rainy season

Treatments	Sampling date		
	4 March 2002	6 April 2002	16 April 2002
	Total inorganic-N (mg kg^{-1})		
Natural fallow	9.1 d	5.0 g	2.9 e
S/A	8.8 de	16.6 a	10.0 a
TSP + S/A	8.0 e	9.2 ef	7.6 cd
MPR + S/A	8.7 de	9.3 ef	8.1 c
T. vogelii biomass	13.2 a	11.9 b	9.0 b
T. vogelii biomass+MPR[1]	11.8 b	8.8 f	7.9 c
T. vogelii biomass + MPR[2]	11.9 b	9.9 de	7.8 c
Treatment 5 + *T. vogelii* relay	12.4 ab	10.4 cd	8.8 b
Treatment 6 + *T. vogelii* relay	11.5 bc	11.0 bc	7.8 c
Treatment 7 + *T. vogelii* relay	10.8 c	10.1 cde	8.1 c
Treatment 4+ *T. vogelii* relay	8.7 de	10.4 cd	7.2 d
Treatment 1 + *T. vogelii* relay	8.8 de	4.8 g	2.9 e
CV (%)	5.4	8.6	7.3

Means bearing the same letter within a column are similar by DMRT at $P\leq0.05$

[1] MPR co-applied with *T. vogelii* biomass at maize planting in 2001/02 season

[2] MPR applied on *T. vogelii* fallow at establishment in 1999/00 season.

Appendix 14. Mineral N dynamics as influenced by *T. vogelii* fallow biomass and MPR applications in 2001/02 rainy season

Treatments	At planting		At vegetative stage		At tasselling stage	
	(mg kg^{-1})					
	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N
1. Natural fallow	5.0 cd	4.1 bc	2.8 c	2.2 d	1.6 c	1.3 c
2. S/A	5.1 cd	3.7 c	9.2 a	7.4 a	5.8 a	4.2 ab
3. TSP + S/A	4.2 d	3.8 c	5.0d	4.2 c	4.0 b	3.6 c
4. MPR + S/A	4.7 d	4.0 bc	5.2cd	4.1 c	4.3 b	3.8 bc
5. *T. vogelii* biomass	7.4 a	5.8 a	6.1 bc	5.8 b	4.7 b	4.3 a
6. *T. vogelii* biomass+MPR[1]	6.3 abc	5.5 a	4.5 d	4.3 c	4.5 b	3.7 c
7. *T. vogelii* biomass + MPR[2]	6.7 ab	5.2 ab	5.5 cd	4.3 c	4.3 b	3.5 c
8. Treatment 5 + *T. vogelii* relay	6.7 ab	5.7 a	6.2 bc	4.2 c	4.6 b	4.2 a
9. Treatment 6 + *T. vogelii* relay	6.2 abc	5.3 ab	5.0 d	6.0 b	4.4 b	3.4 cd
10. Treatment 7 + *T. vogelii* relay	5.6 bcd	5.2 ab	5.5 cd	4.6 c	4.5 b	3.6 c
11. Treatment 4+ *T. vogelii* relay	4.6 d	4.1 bc	5.6 cd	4.8 c	4.0 b	3.2 d
12. Treatment 1 + *T. vogelii* relay	4.6 d	4.2 bc	2.7 e	2.1 d	1.7c	1.2 c
CV (%)	13.98	14.37	11.51	11.88	9.53	6.93

Means bearing the same letter within a column are similar by DMRT at $P \leq 0.05$

[1] MPR co-applied with *T. vogelii* biomass at maize planting in 2001/02 season

[2] MPR applied on *T. vogelii* fallow at establishment in 1999/00 season.

Appendix 15. Influence combined application of MPR with *T. vogelii* biomass on Pi-P in maize field in 2001/02 and 2002/03 seasons

Treatments	Pi-P (mg P g^{-1})	
	16 April 2002	7 June 2003
1. Natural fallow	2.5 g	2.1 f
2. S/A	2.3 g	1.9 f
3. TSP + S/A	13.7 a	6.3 cd
4. MPR + S/A	12.2 b	6.8 abc
5. *T. vogelii* biomass	4.4 f	4.0 e
6. *T. vogelii* biomass+MPR[1]	11.3 bc	7.7 abc
7. *T. vogelii* biomass+MPR[2]	8.5 cde	8.2 a
8. Treatment 5+*T. vogelii* relay[3], biomass [4]	4.8 f	5.2 de
9. Treatment 6+*T. vogelii* relay[3], biomass [4]	9.9 cd	7.3 abc
10. Treatment 7+*T. vogelii* relay[3], biomass [4]	8.3 c	7.0 abc
11. Treatment 4+*T. vogelii* relay[3], biomass [4]	12.6 ab	7.9 ab
12. Treatment 1+*T. vogelii* relay[3], biomass [4]	2.2 g	2.3 f
CV (%)	11.08	17.12

Means bearing the same letter within a column are similar by DMRT at $P \leq 0.05$

[1]MPR applied on *T. vogelii* fallow at establishment in 1999/00 season

[2]MPR co-applied with *T. vogelii* biomass at maize planting in 2001/02 season

[3]*T. vogelii* relay in 2001/02 season

[4]*T. vogelii* biomass applied at 30 kg N ha^{-1} in 2002/03 season.

Appendix 16. Effect of fallow biomass and MPR applications on total inorganic-N in 2002/03 rainy season

Treatments	Sampling date 27 March 2003	7 May 2003
	Total inorganic-N (mg kg^{-1})	
1. Natural fallow	41.9 d	12.8 f
2. S/A	45.2 bc	21.3 b
3. TSP + S/A	39.4 e	16.9 d
4. MPR + S/A	39.5 e	15.7 d
5. *T. vogelii* biomass	47.1 a	20.2 b
6. *T. vogelii* biomass+MPR[1]	42.2 d	18.3 c
7. *T. vogelii* biomass+MPR[2]	44.4 c	13.8 ef
8. Treatment 5+*T. vogelii* relay[3], biomass [4]	46.0 ab	26.4 a
9. Treatment 6+*T. vogelii* relay[3], biomass [4]	41.6 d	14.2 e
10. Treatment 7+*T. vogelii* relay[3], biomass [4]	41.9 d	18.4 c
11. Treatment 4+*T. vogelii* relay[3], biomass [4]	42.9 d	14.2 e
12. Treatment 1+*T. vogelii* relay[3], biomass [4]	39.3 e	16.1 d
CV (%)	10.8	14.7

Means bearing the same letter within a column are similar by DMRT at $P \leq 0.05$

[1]MPR applied on *T. vogelii* fallow at establishment in 1999/00 season

[2]MPR co-applied with *T. vogelii* biomass at maize planting in 2001/02 season

[3]*T. vogelii* relay in 2001/02 season

[4]*T. vogelii* biomass applied at 30 kg N ha^{-1} in 2002/03 season.

Appendix 17. Mineral N dynamics in maize field as influenced by *T. vogelii* fallow biomass and MPR applications in 2002/03 season

Treatments	At vegetative stage		At tasselling stage	
	------------------(mg kg^{-1})-------------			
	NO_3-N	NH_4-N	NO_3-N	NH_4-N
1. Natural fallow	28.2 abc	13.7 c	11.1 b	1.7 c
2. S/A	30.1 a	15.1 abc	18.2 ab	3.1 ab
3. TSP + S/A	23.6 c	15.8 ab	14.7 b	2.2 ab
4. MPR + S/A	25.1 bc	14.4 bc	13.6 b	2.1 bc
5. *T. vogelii* biomass	30.3 a	16.8 a	17.1 ab	3.1 ab
6. *T. vogelii* biomass + MPR[1]	26.6 abc	15.6 abc	15.9 b	2.4 abc
7. *T. vogelii* biomass + MPR[2]	28.9 ab	15.5 abc	12.3 b	1.5 c
8. Treatment 5 + *T. vogelii* biomass[3]	30.2 a	15.8 ab	22.9 a	3.5 a
9. Treatment 6 + *T. vogelii* biomass[3]	26.5 abc	15.1 abc	12.2 b	2.0 bc
10. Treatment 7 + *T. vogelii* biomass[3]	26.8 abc	15.1 abc	15.2 b	3.2 ab
11. Treatment 4+ *T. vogelii* biomass[3]	28.0 abc	14.9 abc	12.3 b	1.94 bc
12. Treatment 1 + *T. vogelii* biomass[3]	23.8c	15.5 abc	14.2 b	1.9 bc
CV (%)	9.51	7.19	24.42	38.22

Means bearing the same letter within a column are similar by DMRT at $P \leq 0.05$

[1]MPR applied on *T. vogelii* fallow at establishment in 1999/00 season

[2]MPR co-applied with *T. vogelii* biomass at maize planting in 2001/02 season

[3]*T. vogelii* biomass applied at 30 kg N ha^{-1} in 2002/03 season.

Appendix 18. First post fallow maize response to fallow biomass and MPR applications

Treatments	Leaf N and P concentration (%)		Maize grain yield	RAE[3]
	N	P	(t ha^{-1})	(%)
1. Natural fallow	2.3c	0.23c	1.64d	
2. S/A	2.8ab	0.27bc	2.35c	
3. TSP + S/A	2.7ab	0.32a	3.45b	100
4. MPR + S/A	3.0a	0.30ab	3.27b	90.1
5. *T. vogelii* biomass	2.8ab	0.28ab	3.28b	90.6
6. *T. vogelii* biomass+MPR[1]	2.7ab	0.31ab	4.05a	133.1
7. *T. vogelii* biomass+MPR[2]	2.7ab	0.31ab	3.36b	95.0
8. Treatment 5 relayed with *T. vogelii*	2.7ab	0.28ab	3.35b	94.5
9. Treatment 6 relayed with *T. vogelii*	2.7ab	0.32a	4.00a	130.4
10. Treatment 7 relayed with *T. vogelii*	2.9a	0.31ab	3.38b	96.1
11. Treatment 4 relayed with *T. vogelii*	2.9ab	0.28ab	3.40b	97.2
12. Treatment 1 relayed with *T. vogelii*	2.2c	0.22c	1.98cd	18.8
CV (%)	7.44	8.55	13.5	

Means and bearing the same letter within a column are similar by DMRT at $P \leq 0.05$.

[1] MPR applied on *T. vogelii* fallow at establishment in 1999/00 season.
[2] MPR co-applied with *T. vogelii* biomass at maize planting in 2001/02 season.

[3] RAE (%)=$\text{Yield}_{\text{treatment}} - \text{Yield}_{\text{control}} / \text{Yield}_{\text{TSP}} - \text{Yield}_{\text{control}} \times 100$

Appendix 19. List of Publications published from this PhD research work

1. **Mkangwa, C.Z.**, Semoka, J.M.R. and Maliondo, S.M.S. (2001). Response of *Tephrosia vogelii* to Minjingu phosphate rock application on a Ferralsol of varying soil pH. *In*: Proceedings of 8^{th} Afnet Conference, Arusha, Tanzania.

2. **Mkangwa, C.Z.**, Semoka, J.M.R. and Maliondo, S.M.S. (2001). Performance of *Tephrosia vogelii* grown on a P deficient Ferralsol amended with Minjingu phosphate rock. *In*: Proceedings of the 19^{th} Conference of the Soil Science Society of East Africa, Moshi, Tanzania.

3. **Mkangwa, C.Z.**, Semoka, J.M.R. and Maliondo, S.M.S. (2002). Nutrient accumulations of 22-months old *Tephrosia vogelii* planted on P deficient Ferralsol applied with Minjingu phosphate rock. *In*: Proceedings of the 20^{th} Conference of the Soil Science Society of East Africa, Mbale, Uganda.

4. **Mkangwa, C.Z.**, Maliondo, S.M.S. and Semoka, J.M.R (2003). Influence of Minjingu phosphate rock applied to *Tephrosia vogelii* fallows on litter and biomass quantity and quality and subsequent maize yields on a Ferralsol in Morogoro. *In*: Proceedings of the 2^{nd} collaborative Research workshop on food Security. Morogoro, Tanzania. pp 97-102.

5. **Mkangwa, C.Z.**, Semoka, J.M.R and Maliondo, S.M.S. (2004). Improvement in *Tephrosia vogelii* biomass yield and quality due to application of Minjingu phosphate rock to ferralsols of different pH. ***Biological Agriculture and Horticulture*** 22 (1), .

6. **Mkangwa, C.Z.**, Semoka, J.M.R. and Maliondo, S.M.S. (2004). Influence of *Tephrosia vogelii* fallow-rotation with maize on soil fertility regeneration in sub-humid climate of eastern Tanzania. *In:* Proceedings of the 21^{st} Conference of the Soil Science Society of East Africa. Eldoret,, Kenya. 1-5 December, 2003.

7. **Mkangwa, C.Z.**, Maliondo, S.M.S. and Semoka, J.M.R (2004). Enhancing nutrient accumulation of *Tephrosia vogelii* fallow through Minjingu phosphate rock application on acidic P deficient ferralsol of eastern Tanzania. ***Submitted to Biological Agriculture and Horticulture.***