

**THE EFFECT OF *Tithonia diversifolia* (HEMSLEY) A. GRAY BIOMASS ON
THE SOLUBILITY OF ROCK PHOSPHATES: A LABORATORY
INCUBATION EXPERIMENT**

**[EFECTO DE LA APLICACIÓN DE *Tithonia diversifolia* (HEMSLEY) A.
GRAY EN LA SOLUBILIDAD DE ROCAS FOSFÓRICAS: EXPERIMENTO
DE INCUBACIÓN DE LABORATORIO]**

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SUMMARY

A 16-week laboratory incubation experiment was conducted to evaluate the effect of *Tithonia diversifolia* leaves on the dissolution of Minjingu (MPR) and Busumbu (BRP) rock phosphates in a Kenyan Oxisol. Triple superphosphate (TSP) fertilizer was included as a positive control. Soil samples were extracted with anion exchange resin (AER) and mixed anion-cation exchange resin (ACER) after 1, 7, 14, 28, 56 and 112 days to estimate plant available P. Soil P fractionation was carried out using solutions of 0.5M NaHCO₃, 0.1M NaOH and 1M HCl. The highest mean AER-extractable P concentrations for BRP and MPR treatments were 6.0 and 20 mg kg⁻¹ respectively; while that of the TSP treatments was 24 mg kg⁻¹. The AER-extractable P concentrations were in the order TSP > MPR > BRP. The ACER-extractable P concentrations were higher than those of AER. Application of tithonia at 10 tons ha⁻¹ in combination with MPR caused a significant (P<0.05) depression in AER-extractable P. The TSP treatments had the highest NaHCO₃-P_i and NaOH-P_i (labile and moderately labile inorganic P) fractions which ranged from 22 to 32% and 45 to 59% of total added P, respectively; followed by MPR treatment which had NaHCO₃-P_i and NaOH-P_i fractions ranging from 13 to 22% and 26 to 34% of the total added P, respectively. Addition of tithonia decreased the NaHCO₃-P_i and NaOH-P_i fractions from the MPR treatments by 2 to 8%. The RP treatments had the highest HCl-P_i (undissolved RP) fraction.

Key words: Extractable phosphorus, rockphosphates, solubilization, *Tithonia diversifolia*

INTRODUCTION

Soil P deficiency is a major constraint to crop production in the densely populated humid highlands of Eastern Africa (Smaling *et al.*, 1993; Jama *et al.*,

RESUMEN

Se efectuó una prueba de incubación en laboratorio de 16 semanas para evaluar el efecto de las hojas de *Tithonia diversifolia* en la disolución de las rocas fosfóricas Minjingu (MPR) y Busumbu (BRP) en un suelo Oxysol de Kenia. Se empleó superfosfato triple (TSP) como control positivo. Las muestras de suelo fueron extractadas con resina de intercambio anionico (AER) y resinas de intercambio mixtas anión-cación (ACER) después de 1, 7, 14, 28, 56 y 112 días para estimar el P disponible para las plantas. El fraccionamiento del P del suelo se realizó con soluciones de 0.5M NaHCO₃, 0.1M NaOH y 1M HCl. La mayor concentración de P extractable en AER para BRP y MPR fue de 6.0 y 20 mg kg⁻¹ respectivamente; mientras que para TSP fue 24 mg kg⁻¹. Las concentraciones de P extractable en AER fueron en el siguiente orden TSP > MPR > BRP. Las concentraciones de P extractable en ACER fueron mayores que aquellas en AER. El empleo de 10 tons ha⁻¹ de tithonia en combinación con MPR causó una depresión (P<0.05) en el P extractable en AER. El tratamiento con TSP tuvo la mayor fracción de NaHCO₃-P_i y NaOH-P_i (P inorgánico lábil y moderadamente lábil) la cual fue de 22 a 32% y de 45 a 59% del total de P añadido, respectivamente; seguido de MPR con las fracciones NaHCO₃-P_i y NaOH-P_i fluctuando de 13 a 22% y de 26 a 34% del total del P añadido, respectivamente. La adición de tithonia causó un decremento de las fracciones NaHCO₃-P_i y NaOH-P_i del tratamiento MPR que fluctuó del 2 al 8%. Los tratamientos de roca fosfórica tuvieron la mayor fracción de HCl-P_i (RP no disuelta).

Palabras clave: Fósforo extractable, roca fosfórica, solubilización, *Tithonia diversifolia*

1997). Insufficient use of P fertilizers to either replace the P exported with harvested plant materials or to correct inherently low levels of soil P has further contributed to depletion of P stocks. The replenishment of soil P stocks requires input of readily

soluble commercial P fertilizers rather than the sole dependence on P cycling through organic-based systems (Mokwunye *et al.*, 1996; Buresh *et al.*, 1997). However, use of commercial P fertilizers is an expensive venture to most resource limited smallholder farms in Eastern Africa.

Direct application of indigenous rock phosphates has been viewed as an attractive option for building soil P fertility because it potentially involves lower production costs and capital investments than the production of water-soluble P fertilizers from indigenous rock phosphate sources (Hammond *et al.*, 1986; Rajan *et al.*, 1996). Sub-Saharan Africa contains numerous rock phosphate deposits, and some are sufficiently reactive for direct application (Buresh *et al.*, 1997). However, most of the rock phosphate deposits in the region are of igneous origin and are unsuitable for direct application due to their low solubility (Van Strateen, 1997).

Various methods have been used to improve the solubility of rock phosphates. They include: partial acidulation with H₂SO₄ or H₃PO₄ (Hammond *et al.*, 1986; Mackay and Wewala, 1990), partial acidulation with elemental S through biological processes (Longanathan *et al.*, 1994), and mixing with soluble P fertilizers (Chien *et al.*, 1987; Kpombrekou *et al.*, 1991). Other materials also found to be effective in enhancing P solubilization when mixed with less reactive rock phosphates re organic acids and animal manures (Ikerra, 1994; Mahimairaja *et al.*, 1994). The products of decomposition of manures include simple and complex organic acids (Stevenson, 1994) which reacts with Ca in the apatite thus, allowing P to solubilize with ease. However, there is little information in the literature, on the use of green manures to enhance the solubility of rock phosphates. The objective of this research work was therefore, to evaluate the effect of *Tithonia diversifolia* (Tithonia) leaves on the solubility of P from rock phosphates (RP) in a Kenyan Oxisol.

MATERIALS AND METHODS

The soil used for this study was a Kandiuialfic Eudrudox (USDA, 1992) collected from Western Kenya, and had the following characteristics in the top 0.15m: pH (1:2.5 soil/water suspension) = 5.2, exchangeable acidity = 0.5 cmol kg⁻¹, organic carbon (C) = 17.0 g kg⁻¹, exchangeable calcium (Ca) = 4.1 cmol kg⁻¹, exchangeable magnesium (Mg) = 1.4. cmol kg⁻¹, exchangeable potassium (K) = 0.08 cmol kg⁻¹, bicarbonate-ethylenediaminetetraacetic acid (EDTA) extractable P = 1 mg kg⁻¹, clay = 39% and sand = 30%. Organic C was determined by wet oxidation method with heated acid-dichromate followed by calorimetric determination of Cr³⁺ (Anderson and Ingram, 1993). Extractable P and exchangeable K were determined by

extraction with 0.5M NaHCO₃ + 0.01M EDTA (pH 8.5). Exchangeable Ca, Mg and acidity were determined by extraction with 1M KCl. Phosphorus sorption isotherms determined by the Fox and Kamprath (1970) method indicated that a soil solution P concentration of 0.2 mg P L⁻¹ corresponded to 260 mg sorbed P kg⁻¹.

Minjingu rock phosphate (MRP) (12.8% total P, 3.03% neutral ammonium citrate soluble P, and 26.9% Ca) from Tanzania, Busumbu rock phosphate (BRP) (5.6% total P, 0.51% neutral ammonium citrate soluble P and 29% Ca), and Triple Superphosphate (TSP) (20% P) were the sources of P used in this study. The MRP and BRP were applied as finely ground powder (>90% passing 100-mesh sieve) and TSP was applied in commercially available granular form. The source of green manure was leaf biomass of tithonia [*Tithonia diversifolia* (Hemsley) A. Gray] which were added after grinding to less than 100 µm. Leaf samples analyzed using the ICRAF Laboratory Methods for Soil and Plant Analysis (1994) contained 41800 mg N kg⁻¹, 46100 mg K kg⁻¹, 3830 mg P kg⁻¹, 4180 mg Mg kg⁻¹, 1832 mg Ca kg⁻¹, 6.48% Lignin and 1.59% TAE.

Incubation Experiment to assess the effect of *T. diversifolia* and P release from different inorganic sources

A laboratory incubation study was carried out using 150-g air-dry soil samples which were thoroughly mixed with tithonia, MRP, BRP or TSP in factorial combinations, in 500 mL glass bottles. Tithonia was added at the rate of 2 and 10 tons ha⁻¹ corresponding to 4.2 and 21 mg P kg⁻¹ soil respectively. Minjingu rock phosphate was applied at 150 kg P ha⁻¹ or 91 mg P kg⁻¹ soil, and BRP was applied at 88 kg P ha⁻¹ or 53 mg P kg⁻¹ soil. The intent was to apply BRP at the same rate as MRP but it was discovered later that the lot of BRP used was different from the one analyzed prior to the study. Triple Superphosphate was applied at 75 and 150 kg P ha⁻¹ corresponding to 45.5 and 91 mg P kg⁻¹ soil, respectively. The treatments included: Control (soil only), Tithonia 2 tons ha⁻¹, Tithonia 10 tons ha⁻¹, Minjingu 150 kg P ha⁻¹, Minjingu 150 kg P ha⁻¹ + Tithonia 2 tons ha⁻¹, Minjingu 150 kg P ha⁻¹ + Tithonia 10 tons ha⁻¹, TSP 150 kg P ha⁻¹, TSP 150 kg P ha⁻¹ + Tithonia 2 tons ha⁻¹, TSP 150 kg P ha⁻¹ + Tithonia 10 tons ha⁻¹, Busumbu 88 kg P ha⁻¹, Busumbu 88 kg P ha⁻¹ + Tithonia 2 tons ha⁻¹, Busumbu 88 kg P ha⁻¹ + Tithonia 10 tons ha⁻¹, Busumbu 88 kg P ha⁻¹ + TSP 75 kg P ha⁻¹, Busumbu 88 kg P ha⁻¹ + TSP 75 kg P ha⁻¹ + Tithonia 2 tons ha⁻¹ and, Busumbu 88 kg P ha⁻¹ + TSP 75 kg P ha⁻¹ + Tithonia 10 tons ha⁻¹. The soil was moistened to 60% of its water holding capacity and the bottles closed tightly. The bottles were kept in the dark for 1, 7, 14, 28, 56 and 112 days at 23°C. All the treatments were replicated three times in a completely

randomized design. After each period of time triplicate soil samples were analyzed as follows:

Comparisons between different P extraction techniques

Anion resin extractable P was determined by shaking 2.5 g of soil for 16 h with 40 ml of deionized water and one mesh bag containing 1 g Dowex 1-X8 anion exchange resin (AER) converted to bicarbonate form (Sibbesen, 1978). Phosphorus extracted with mixed resin was determined by shaking 2.5 g of soil for 16 h with 40 mL of deionized water and one mesh bag with the anion exchange resin plus one mesh bag containing 1 g Amberlite 1R-120 cation exchange resin (CER) in sodium form. The P adsorbed by the resin in the anion and mixed resin (AER + CER) methods was extracted by shaking the resin bag with 20 mL of 0.5M HCl for 1 h.

Bicarbonate extractable P was determined by shaking 2.5 g of soil for 30 mins with 50 mL of 0.5M NaHCO₃ (pH 8.5). Sodium hydroxide extractable P was determined by shaking 0.5 g of soil with 25 mL of 0.1M NaOH overnight and then centrifuging at 5,700 x g for 10 min. An aliquot of the NaOH extract was acidified with 0.6 mL of 1.2M H₂SO₄ and centrifuged for 10 min to precipitate organic matter. The supernatant was then analyzed for inorganic P (P_i). Aliquots of bicarbonate and NaOH extracts were digested with acidified ammonium persulfate in an autoclave (103 kPa, 121°C) for 1 h and then analyzed for total P (P_t). Extractable organic P (P_o) was calculated as the difference between P_t and P_i. The NaOH fraction was determined on a separate soil sample rather than in sequence with the resin and bicarbonate extractions (Tiessen and Moir, 1993).

After extraction with NaOH and decanting the supernatant, soils were sequentially analyzed for dilute acid extractable P_i by shaking for 16 h with 30 mL of 1M HCl. The extract was then filtered and neutralized with NaOH. The P concentration in all extracts and digests was determined by the colorimetric method of Murphy and Riley (1962). All laboratory analyses were conducted in triplicate. The increase in soil P following P application was determined as the difference in the soil fraction P between the added P treatment and the no added P control.

The efficiency of the different extractant systems was tested by extracting for 16 h, triplicate samples of Minjingu and Busumbu rock phosphates equivalent to

150 kg P ha⁻¹, by all the above methods without soil, using extractant solutions or water plus resin only, in order to test the solubility characteristics of the rock phosphates.

Data processing and statistical analyses were performed with the aid of the Statistical Analysis Systems (SAS, 1994) and the Excel statistical functions (Excel, 1994).

RESULTS

Changes in resin-extractable phosphorus after incubation

Maximum values of resin P (AER and AER + CER) were obtained at the initial extraction (week 0) for all soil-P combinations (Table 1 and 2). The levels of resin-extractable P decreased with time in all the treatments. The TSP treatment has the highest mean AER-P concentration of 24 mg P kg⁻¹. The mean AER-P values for the BRP and MRP treatments were 6 and 20 mg P kg⁻¹ respectively. The mean AER-P values were ranked in the order: TSP>MRP>BRP, which was consistent with the citrate solubility of the two rock phosphates. The AER-P for triple superphosphate treatment alone was significantly higher than that of MRP alone (Table 1). The difference in AER-P between the TSP and MRP treatments decreased with time and there were significant differences between the two P sources by week 8 (Table 3).

No significant changes were observed when TSP was applied in combination with tithonia. The MRP plus tithonia (10 ton ha⁻¹) treatment had significantly lower AER-P than MRP treatment alone at all the six sampling times except week 16 (Table 3). The MRP plus tithonia (2 ton ha⁻¹) treatment resulted in a slight depression in AER-P, although not significantly different from MRP treatment alone (Table 3).

The mixed resin (AER + CER) extracted more P than the anion resin following rock phosphate application. The MRP treatment alone had a significantly high resin (AER + CER) - P than TSP treatments alone at all the six sampling dates (Table 3). Application of BRP resulted in a significantly high resin-P (AER and mixed resin) than the controls at all the six sampling times. However, the treatment that received tithonia at 2 and 10 ton ha⁻¹ plus BRP were not significantly different from those that received BRP alone.

Table 1. The amount of P extracted with anion resin at various times of incubation (mg kg⁻¹).

Treatments	Incubation Period (Weeks)					
	0	1	2	4	8	16
Control	2.1	2.4	2.3	2.3	1.9	1.9
Tithonia 2 tons ha ⁻¹	2.0	2.4	2.1	2.7	2.3	2.2
Tithonia 10 tons ha ⁻¹	3.8	3.9	3.3	4.7	3.5	3.6
Minjingu 150 kg P ha ⁻¹	29	25	22	22	22	20
Minjingu 150 kg P ha ⁻¹ + Tithonia 2 tons ha ⁻¹	30	24	20	21	20	21
Minjingu 150 kg P ha ⁻¹ + Tithonia 20 tons ha ⁻¹	23	20	18	19	19	21
TSP 150 kg P ha ⁻¹	35	23	22	22	20	22
TSP 150 kg P ha ⁻¹ + Tithonia 2 tons ha ⁻¹	32	24	19	23	22	20
TSP 150 kg P ha ⁻¹ + Tithonia 10 tons ha ⁻¹	35	25	26	27	22	20
Busumbu 88 kg ha ⁻¹	5.4	4.7	4.4	5.9	5.6	5.7
Busumbu 88 kg P ha ⁻¹ + Tithonia 2 tons ha ⁻¹	5.3	5.2	4.9	5.2	5.3	6.1
Busumbu 88 kg P ha ⁻¹ + Tithonia 10 tons ha ⁻¹	4.5	5.4	6.8	5.5	5.9	6.4
Busumbu 88 kg P ha ⁻¹ + TSP 75 kg P ha ⁻¹	15.2	15	13	13	14	13
Busumbu 88 kg P ha ⁻¹ + TSP 75 kg P ha ⁻¹ + Tithonia 2 tons ha ⁻¹	15.7	15	11	15	12	13
Busumbu 88 kg P ha ⁻¹ + TSP 75 kg P ha ⁻¹ + Tithonia 10 tons ha ⁻¹	17	17.2	15	14	18	14

Table 2. The amount of P extracted with anion plus cation resin (mg P kg⁻¹) at various times of incubation.

Treatments	Incubation Period (Weeks)					
	0	1	2	4	8	16
Control	3.3	2.3	3.3	3.1	2.7	2.5
Tithonia 2 tons ha ⁻¹	3.3	2.7	3.5	3.3	3.0	3.1
Tithonia 10 tons ha ⁻¹	5.3	4.0	5.5	5.1	4.7	4.5
Minjingu 150 kg P ha ⁻¹	43	34	35	31	32	29
Minjingu 150 kg P ha ⁻¹ + Tithonia 2 tons ha ⁻¹	42	37	38	33	32	29
Minjingu 150 kg P ha ⁻¹ + Tithonia 20 tons ha ⁻¹	39	35	41	36	34	33
TSP 150 kg P ha ⁻¹	36	25	27	26	28	27
TSP 150 kg P ha ⁻¹ + Tithonia 2 tons ha ⁻¹	33	31	27	27	28	26
TSP 150 kg P ha ⁻¹ + Tithonia 10 tons ha ⁻¹	36	28	32	30	28	26
Busumbu 88 kg ha ⁻¹	12	11	12	9.9	10	11
Busumbu 88 kg P ha ⁻¹ + Tithonia 2 tons ha ⁻¹	13	11	13	9.9	11	11
Busumbu 88 kg P ha ⁻¹ + Tithonia 10 tons ha ⁻¹	15	13	13	11	13	14
Busumbu 88 kg P ha ⁻¹ + TSP 75 kg P ha ⁻¹	20	18	17	18	18	19
Busumbu 88 kg P ha ⁻¹ + TSP 75 kg P ha ⁻¹ + Tithonia 2 tons ha ⁻¹	21	19	21	19	20	18
Busumbu 88 kg P ha ⁻¹ + TSP 75 kg P ha ⁻¹ + Tithonia 10 tons ha ⁻¹	24	21	25	21	24	21

Sequential fractionation for organic and inorganic soil phosphorus fractions

Inorganic P fractions (P_i) extracted sequentially were greater for TSP than for MRP treatments (Table 4). Both NaHCO₃-P_i and NaOH-P_i fractions were significantly higher (P<0.001) in the TSP than in the MRP treatments. Within 2 weeks, 21% of P added as MRP was recovered in the NaHCO₃-P_i fraction and 28% in the NaOH-P_i fraction (Table 4). However,

after week 16, there were no significant changes in the amounts of extractable P.

Application of tithonia in combination with MRP resulted in less extractable P than was expected. Assuming the expected amount of extractable P is the total P extracted from the separate MRP and tithonia treatments less P extracted from the control treatment, dissolved P fractions extracted as NaHCO₃-P_i and NaOH-P_i were significantly low; whereas, undissolved P fraction (HCL-P_i) was significantly high (Table 5).

The addition of tithonia increased recovery in the HCl-P_i fraction from 11% (MRP) to 21% (MRP + tithonia). The organic P fractions (P_o) tended to be greater in the tithonia plus inorganic P treatments than in the inorganic P treatments alone, although the differences were not significant (Table 5). The results for the 16-week sampling showed a similar trend to those of the

2-week sampling. Addition of tithonia to BRP did not improve its low solubility throughout the 16-week incubation period (Table 5). Although the P_o fractions in the BRP plus tithonia treatment were higher than BRP alone treatments, the differences were not significant.

Table 3. Difference in resin extractable P between treatment means of the inorganic and a combination of organic and inorganic P sources compared to the organic and inorganic P sources applied alone.

Incubation period (weeks)	Resin method	Treatment Comparison ¹						
		TSP and MRP	(TSP + T ₂) and TSP ₂ +T	(MRP+T ₁) and MRP+T ₁	(MRP+T ₂) and MRP+T ₂	BRP and control	(BRP+T ₁) and BRP+T ₁	(BRP+T ₂) and BRP+T ₂
0	AER	7.2***	-1.6	1.0	-7.3**	3.3*	0	-2.6
	ACER	-6.6***	-2.4	-0.5	-0.4	8.8***	0.8	0.4
1	AER	1.3	1.1	-0.5	-5.9*	2.3	0.5	-0.8
	ACER	-7.4***	2	1.9	-0.8	9.3***	-0.6	-0.2
2	AER	2.6***	2.8	-2.3	-5.4**	2.1	0.6	1.3
	ACER	-9.4***	3.5	2.7	3.6	9.0***	0.1	-1.1
4	AER	3.2***	2	-2	-5.7***	3.5***	-0.1	-2.7*
	ACER	-5.5***	2.2	2.2	2.9	6.9***	-0.2	-0.8
8	AER	0.9	0.5	-2.5	-4.7*	3.6*	-0.7	-1.3
	ACER	-4.6***	-1.4	-0.5	-0.1	7.6***	0.1	0.8
16	AER	-0.1	-3.7**	0.6	-1.3	3.8***	0	-1
	ACER	-4.1***	-2.7	-0.8	1.3	8.7***	-0.8	0.9

¹Differences between treatments were determined by single degree of freedom contrasts; AER= Anion exchange resin; ACER=Anion and cation exchange resin; T₁=Tithonia at 2 tons ha⁻¹; T₂ = Tithonia at 10 tons ha⁻¹; MRP = minjingu rock phosphate; BRP = Busumbu rock phosphate; ØBrackets indicate combined organic and inorganic sources; contrasted with organic and inorganic sources applied alone; *, **, and *** designates significance at P<0.05, p<0.01 and p<0.001, respectively.

DISCUSSION

Resin-extractable phosphorus after incubation

Soils treated with TSP had more AER-P than MRP-treated soils on day 1 of incubation. This was attributed to the high solubility of TSP which rapidly forms reaction products after application to the soil; whereas, addition of MRP releases P more slowly due to its low solubility (Chien *et al.*, 1987). The decrease in AER-P from TSP after day 1 of incubation may be attributed to the immediate provision of a relatively high soil solution P that might favour a rapid adsorption of the P onto soil components (Chien *et al.*, 1987).

It is apparent that the AER-P of the reactive MRP was depressed by the addition of tithonia. This was

probably due to the Ca²⁺ released by the tithonia during decomposition, which may have increased the Ca²⁺ concentration in the soil solution above that due to solubilization of RP alone; thereby, reducing the RP solubility through mass action. Zaharah and Bah (1997) observed a similar depression in the solubility of reactive Algerian RP following incorporation of green manures. During week 1 and thereafter, amounts of AER-P extracted from MRP and TSP were similar. The high dissolution of MRP in the soil could be attributed to the soil's acidic nature, low extractable P, high sorption capacity and low exchangeable Ca. The dissolution of RP and hence, its effectiveness increases with increasing acidity in soils (Hammond *et al.*, 1986). The biogenic nature of origin and the relatively high neutral ammonium citrate soluble P of the MRP (24% of the total P), may also have probably contributed to the high dissolution.

Table 4. Extractable P fractions and recoveries from the various P sources after 2 and 16 weeks of aerobic incubation (WAI).

WAI	Treatment	Total added P (mg kg ⁻¹)	Net extractable P (treatment - control) (mg kg ⁻¹)					Recovery (%)			
			NaHCO ₃ P _i	NaHCO ₃ -P _o	NaOH-P _i	NaOH-P _o	HCl-P _i	NaHCO ₃ -P _i	NaOH-P _i	HCl-P _i	
2	Tithonia	21	2	3	7	3	3	26	44	15	
	Minjingu	91	13	6	29	-4	10	21	28	11	
	Minjingu+tithonia	112	8	6	20	10	23	13	26	21	
	TSP	91	24	5	42	7	2	32	54	2	
	TSP+tithonia	112	26	7	5	-1	8	15	7	15	
	Busumbu	53	1	7	5	-1	8	15	7	15	
	Busumbu+tithonia	75	3	9	7	10	11	16	23	14	
	TSP	72	12	10	25	9	8	31	31	4	
	Busumbu+tithonia	93	14	11	32	7	8	27	42	9	
	TSP+Tithonia										
16	Tithonia	21	2	3	7	0	2	24	30	8	
	Minjingu	91	16	4	34	-8	9	22	29	9	
	Minjingu+tithonia	112	17	4	32	6	19	19	34	17	
	TSP	91	24	2	45	-4	2	29	45	2	
	TSP+tithonia	112	22	3	50	5	3	22	49	3	
	Busumbu	53	3	4	8	-7	7	14	1	14	
	Busumbu+tithonia	75	4	5	9	-2	9	13	9	12	
	Busumbu+tithonia	72	12	5	26	-6	3	22	28	4	
	TSP										
	Busumbu+tithonia	93	14	7	32	-2	5	22	33	6	
TSP+tithonia											

¹Tithonia applied at the rate of 10 tons ha⁻¹; NaHCO₃-P_i = sodium bicarbonate extractable inorganic P; NaHCO₃-P_o = sodium bicarbonate extractable organic P; NaOH-P_i = sodium hydroxide extractable inorganic P; NaOH-P_o = sodium hydroxide extractable organic P; HCl-P_i = hydrochloric acid extractable inorganic P.

Table 5. Extractable P from some selected treatment combinations compared with expected values (assuming a purely additive effect)

Treatment	Differences in measured extractable P fractions				
	Measured – Expected# (mg kg ⁻¹)				
	NaHCO ₃	NaOH		HCl	
	P _i	P _o	P _i	P _o	P _i
Minjingu + Tithonia (10 tons ha ⁻¹)	-7***	-3 ns	-16***	11 ns	10**
Busumbu + Tithonia (10 tons ha ⁻¹)	-1 ns	-1 ns	-5 ns	10 ns	-1 ns
Busumbu + TSP	0 ns	5 ns	2 ns	-5 ns	-2 ns

#Measured values refers to the extractable P from rock phosphate plus tithonia treatment.

+Expected value is the sum of extractable P from rock phosphate treatment only and tithonia treatment only, assuming a purely additive effect.

, * indicates significance at 0.01 and 0.001 probability levels, respectively.

The mixed resin (AER + CER) extracted more inorganic P in all the soils treatments, with RP treatment being higher than the TSP treatment. The CER may have acted as a Ca sink, thereby enhancing the extraction of P by decreasing the Ca activity in the soil solution (Saggar *et al.*, 1992a, b). The CER may also have directly enhanced the RP dissolution during extraction (Robinson and Syers, 1990). This is supported by the proportionately higher amounts of P extracted by the mixed resin than that extracted by the AER alone, in the RP treatment compared to the TSP treatment.

The moderately high P sorption capacity of this soil (300 mg P kg⁻¹ soil at 0.2 mg P/L solution) is more than the maximum amount of resin P released dissolution, which suggests that there was a sufficiently large P sink for the complete of P released from RP. In the absence of an additional sink for Ca²⁺, the concentration of Ca²⁺ in the soil solution would have increased, and therefore, prevented the dissolution of RP. Saggar *et al.*, 1992a, b) also reported that the increase in extractable P on inclusion of a mixed resin system in soil was due to an additional Ca sink by CER. However, the mixed resin did not enhance P extraction in the TSP treatment. The effect of Ca²⁺ in solution therefore, seems to be minimal, suggesting that the direct dissolution effect is more important.

Assuming NaHCO₃-P_i and NaOH-P_i fractions approximate the amount of TSP, MRP and BRP that dissolved (86%, 49% and 22% respectively), the amounts of Ca added to the soil due to TSP, MRP and BRP dissolution were 0.26, 0.47 and 0.30 cmol kg⁻¹, respectively, Calcium saturation of the effective cation exchange capacity (sum of base plus exchangeable acidity) of the soil due to the application of TSP, MRP and BRP was 72%, 75% and 72% respectively. It was evident that inclusion of a mixed resin system enhanced P dissolution and consequently extraction from RP source. The AER-P from the BRP was low which was in agreement with the low neutral ammonium citrate soluble P of the BRP (9% of the total P). We postulate that the low solubility of the BRP was probably due to the varying extents of carbonate substitution in the RP. Chemical analyses results indicated that the BRP was a low-carbonate substituted variety of igneous origin, which has been shown to have low reactivity in acids, solvents and soils.

Sequential soil P fractions

The concentration of phosphorus in the soil following application of TSP was initially high, probably due to a rapid and relatively complete reaction with an acid soil, which resulted in the formation of Fe and Al phosphate compounds (NaHCO₃-P_i and NaOH P_i).

The high recovery of P in TSP treatment (96%) as NaHCO₃-P_i and NaOH P_i supports this view (Table 4). Due to the slow dissolution of RPs, the amount of NaHCO₃-P_i and NaOH P_i from these sources was low. However, after 2 weeks of incubation, 49% of added P as MRP compared to only 22% of P as BRP was recovered in the NaHCO₃-P_i fractions, which suggested that MRP was more soluble. The HCl-P fraction, which mainly associated with insoluble Ca-P compounds such as hydroxyapatite (William *et al.*, 1980), estimated the amount of undissolved RP in the soil, because P in RP is considered to be present in the form of calcium apatite. However, the HCl-P underestimated the remaining undissolved P in the soil amended with RP alone. Recently, Mutuo *et al.*, (1999) made similar observations using a similar soil; they obtained a P recovery of only 37% in the Hcl fraction. The generally low total P recoveries for the Rps (60% for MRP and 37% for BRP) compared to 88% for TSP further attest to this finding.

According to the law of mass action, RP dissolution is enhanced by low pH, exchangeable Ca and soil solution P. The decrease in dissolution of MRP upon addition of tithonia may have been due to the added Ca from the decomposition of tithonia, which increased the Ca concentration in soil solution. This may also explain the increase in the HCl-P fraction in MRP plus tithonia treatment. Application of 10 tons tithonia ha⁻¹ added about 0.32 cmol of Ca kg⁻¹ soil, thereby increasing the Ca saturation of the soil exchange complex from 67 to 73%. This amount is two thirds of that already added by the dissolving MRP (49% dissolved within 2 weeks, resulting in Ca content of 26.9%.

Another possible explanation is that the P released may have been incorporated into the organic fraction and hence, rendered unavailable. There is some evidence for this; the RP plus tithonia treatment showed an increase in the NaOH-P_o fraction though it was not significant.

CONCLUSIONS

The MRP was an effective source of P compared to the BRP. Addition of tithonia to the BRP had no effect on P solubility. The solubility of the more reactive MRP was depressed upon the addition of tithonia, probably due to increased Ca concentration in the soil solution. However, direct application of MRP as a source of P on acid soils in East Africa require an agronomic assessment.

ACKNOWLEDGEMENT

We are grateful to the Swedish Agency for Research Cooperation (SAREC), Tropical Soil Fertility and Biology (TSBF) and International Center for Research

in Agroforestry (ICRAF) for financial support to this study. The cooperation and technical assistance of the ICRAF laboratory staff and Dr. Generose Nzinguheba is gratefully acknowledged.

REFERENCES

- Anderson, J.M. and Ingram, J.S. 1993. Tropical Soil Biology and Fertility: A handbook of methods, CAB International, Wellingford, England.
- Bolan, N.S., White, R.E. and Hedley, M.J. 1990. A review of the use of phosphate rocks as fertilizers for direct application in Australia and New Zealand. *Australian Journal of Experimental Agriculture*. 30:297-313.
- Buresh, R.J., Smithson, P.L. and Hellums, D.T. 1997. Building soil P capital in sub-Saharan Africa. In R.J. Buresh and P.A. Sanchez (eds). *Replenishment Soil Fertility in Africa*. pp 111-149. SSSA Special Publication 51. SSSA and ASA, Madison, Winconsin., USA.
- Chien, S.H., Adams, F., Khasawneh, F.E. and Henao, O. 1987. Effects of combination of triple superphosphate and a reactive phosphate rock on yield and phosphorus uptake by corn. *Soil Science Society America Journal*. 51:1656-1658.
- Excel, 1994. Excel Statistical Program. Version 5.0. Microsoft Corp., Seattle, WA.
- Fox, R.J., and Kamprath, E.J. 1970. Phosphate sorption isotherms for evaluating the phosphate requirements of soil. *Soil Science Society America Proceedings*. 34:902-907.
- Hammond, L.L., Chien, S.H. and Mukwenya, A.V. 1986. Agronomic value of unacidulated and partially acidulated phosphate rocks indigenous to the tropics. *Advances in Agronomy*. 40:9-140.
- ICRAF, 1994. Laboratory Methods for Soil and plant Analysis. International Centre for Research in Agroforestry. Nairobi, Kenya.
- Ikerra, T.W.D., Mnekeni, P.N.S. and Singh, B.R. 1994. Effects of added compost and farmyard manure on P release from Minjingu phosphate rock and its uptake by maize. *Norwegian Jorunal Agricultural Science*. 8:13-23.
- Jama, B., Swinkels, R.A. and Buresh, R.J. 1997. Agronomic and economic evaluation of organic and inorganic sources of phosphorus in Western Kenya. *Agronomy Journal*. 89:597-604.
- Kpomblekou, K., Chien, S.H., Henao, J. and Hill, W.A. 1991. Greenhouse evaluation of phosphate fertilizers produced from Togo phosphate rocks. *Communications in Soil Science and Plant Analysis*. 22:63-73.
- Loganathan, P., Hedley, M.J. and Bretherton, M.R. 1994. The agronomic value of co-granulated Christmas Island Grade C phosphate rock and elemental sulphur. *Fertilizer Research*. 39:229-237.
- Mackay, A.D. and Wewala, G.S. 1990. Evaluation of partially acidulated phosphate fertilizers and reactive phosphate rocks for hill pastures. *Fertilizer Research*. 21:149-156.
- Mahimairaja, S., Bolan, N.S. and Hedley, M.J. 1995. Dissolution of phosphate rock during the composting of poultry manure: An incubation experiment. *Fertilizer Research*. 40:39-104.
- Mokwunye, A., Dejaeger, A. and Smaling, E.N.A. 1996. Restoring and maintaining the productivity of West Africa soils: key to sustainable development. IFDC-Africa. pp 94.
- Murphy, J. and Riley, J.P. 1962. A modified single extraction solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta* 27:31-36.
- Rajan, S.S.S., Watkinson, J.H. and Sinclair, A.G. 1996. Phosphate rocks for direct application to soils. *Advances in Agronomy*. 57:77-159.
- Robinson, J.S. and Syers, J.K. 1990. A critical evaluation of factors influencing the dissolution of Gafsa phosphate rock. *Journal of Soil Science*. 41:597-605.
- Saggar, S., Hedley, M.J. and White, R.E. 1992a. Development and evaluation of an improved soil test for phosphorus I. The influence of phosphorus fertilizer solubility and soil properties on the extractability of soil P. *Fertilizer Research*. 33:81-91.
- Saggar, S., Hedley, M.J., White, R.E., Gregg, P.E.H., Perrot, K.W. and Conforth, I.S. 1992b. Development and evaluation of an improved soil test for phosphorus II. comparison of the Olsen and mixed cation-anion exchange resin tests for predicting the yield of ryegrass

- grown in pots. Fertilizer Research. 33:135-144.
- SAS Institute Inc. 1994. SAS/STAT Users' Guide. Volume 2, Version 6.1. SAS Institute Inc. Cary, North Carolina, USA.
- Sibbesen, E. 1978. An investigation of the anion-exchange resin method for soil phosphate extraction. Plant and Soil. 50:305-321.
- Smaling, E.M.A., Nandwa, S.M. and Janssen, B.H. 1997. Soil fertility in Africa is at stake. pp. 47 - 61. In R.J. Buresh, P.A. Sanchez and F. Calhoun (eds). Replenishment Soil Fertility in Africa. SSSA Special Publication 51. Soil Science Society of America, Madison, WI.
- Stevenson, F.J. 1994. Humus chemistry, Genesis, composition, Reactions. 2nd Ed. John Wiley and Sons Inc., New York, USA.
- Tiessen, H. and Moir, J.O. 1993. Characterization of available phosphorus by sequential extraction. In: M.R. Carter (ed) Soil Sampling and Methods and analysis. Lewis Publ., Ann Arbor, Michigan, USA
- United States Department of Agriculture (USDA) 1992. Soil Taxonomy. Agric. Handbook no. 294, Washington, D.C., USA.
- Van Straten, P. 1997. Geological Phosphate Resources in Central East Africa. Trip report, June 23rd-July 21 1997.
- Williams, J.D.H., Mayers T. and Nriagu, J.O. 1980. Extractability of phosphorus from phosphate minerals common in soils and sediments. Soil Science Socociety of America Journal. 44:462-465.
- Zaharah, A.R. and Bah, A.R. 1997. Effect of green manures on solubilization and uptake from phosphate rocks. Nutrient Cycling in Agrosystems. 48:247-255.

Submitted January 09, 2004 -- Accepted July 25, 2004