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Dissolution and effectiveness of phosphate rock in acidic soil amended with cattle manure

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Abstract

Phosphate rock (PR) and organic manure (OM) are promising amendments to acidic soils to correct P deficiency and Al/Mn toxicities. The interaction between PR and OM and consequent effects in acidic soil are not fully understood. The effects of OM on the dissolution of two types of PR (NCPR, North Carolina PR; SYPR, Syrian PR) and dry matter production and nutrient uptake efficiency in an acidic Lily loamy soil from West Virginia were examined in an incubation and plant pot studies. NCPR and SYPR were supplied at a rate of 500 mg P kg^{-1} and organic manure at a rate of 30 g kg^{-1}. Observations were made over 126 days at 21-day intervals. The dissolution of applied NCPR and SYPR was calculated based on the estimation of ?Pi and ?TP-NaOH method. Dissolution of NCPR and SYPR calculated by ΔTP-NaOH was quick during the initial 21 day (∼20%), and thereafter increased slowly reaching 42 and 40% at 126 day for NCPR and SYPR, respectively. On the other hand, percent dissolution calculated based on ΔPi-NaOH, while fluctuating within ±5% between intervals, were less by 10 and 15% at 126 day for NCPR and SYPR compared to dissolutions estimated based on Δ-TP-NaOH. OM generally reduced PR dissolution, and to a 11–14% lesser extend in the presence of plant roots, presumably due to plant roots depleting P and Ca from the dissolution zone. OM increased dry matter production (DM) of switch grass, increased specific accumulation rates (SAcR, mg or μg g^{-1} DM) of P and Mg in shoots, decreased SAcRs of Al and Mn in shoots DM, and increased use of P from NCPR and SYPR. Approximately 29% of dissolved P from applied NCPR or SYPR was Bray-1 extractable-Pi and increasing to 45% when OM was also amended to the soil. This increase in dissolved P probably explains the enhanced growth and P concentration in switch grass DM.

Abbreviations: PR – phosphate rock; OM – organic/cattle manure; NCPR – North Carolina phosphate rock; SYPR – a Syrian phosphate rock; Pi – inorganic phosphorus, Po – organic phosphorus; TP – total phosphorus (Pi+Po); SAcR – specific accumulation rate

Introduction

Problems associated with acidic soils, primarily P and Ca deficiency, and Al toxicity, limit crop production throughout the world (Marschner, 1991). Thus, application of P fertilizer and lime is common practice for achieving high crop yield. In some soils and environments, and some crop species, the use of phosphate rock (PR) in acidic soils can more economically correct P deficiency than manufactured P fertilizer (Rajan et al., 1991). However, application of limestone significantly inhibits PR dissolution (He et al., 1996a, b), which was attributed to an increase in pH and exchangeable Ca in the soil. This finding is not surprising, considering the hypothetical PR dissolution reaction (Khasawneh and Doll, 1978), resulting in the release of $H_2PO_4^-$ and Ca^{2+}.

$$Ca_{10}(PO_4)6F_2 + 12H^+ \rightleftharpoons 10Ca^{2+} + 6H_2PO_4^- + 2F^- \quad (1)$$

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According to Equation (1), the dissolution of PR can be increased by increasing the supply of protons (H^+) or by the continuous removal of the dissolved Ca and P from the dissolution zone (Kirk and Nye, 1986). Both of these expected processes have been shown to increase the dissolution of PR when acidic soil is amended with organic matter, such as cellulose (He et al., 1996a), or poultry manure (Mahimairaja et al., 1995). With the later amendment, protons are supplied by organic acids produced during composting and by the oxidation of ammonium to nitrate in manure which was shown to enhance PR dissolution as estimated by the ΔP-NaOH method (Mahimairaja et al., 1995). However, neither starch nor farmyard manure significantly increased P availability from PR applied to acidic soil (Basak and Debnath, 1987).

Most of the P dissolved from PR undergoes immediate adsorption and immobilization reactions, whereas only a fraction (30–50% of dissolved P from PR) becomes available for plant uptake (Bolan and Hedley, 1990; Kanabo and Gilkes, 1987). These authors demonstrated a close relationships between the amount of $NaHCO_3$ extractable P and P taken up by plants. However, P extracted with citric acid, water, Bray, and $NaHCO_3$ (Bangar et al., 1985; Mishra and Bangar, 1986; Singh and Amberger, 1991) underestimate PR dissolution. The use of 0.5 *M* NaOH as an extractant (Mackay et al., 1986), as modified by He et al. (1996a), extracts P released from PR dissolution, most of which is sorbed by sesquioxides, oxides, or precipitated as Fe and Al phosphates in acid soils. Using this procedure, both the sorbed P and newly formed Fe and Al phosphates can be extracted. In these studies, dissolved P from PR was measured colorimertically by an ascorbic acid-phosphomolybdate method (Olsen and Sommers, 1982). This method determines only inorganic P (Pi) in the 0.5 *M* NaOH extract, which probably underestimates total P dissolution from applied PR to the soil, as it does not include the organic fraction of dissolved P associated with organic compounds in the soil. The organic fraction of P (Po) constitutes over 50% of total P extracted in 0.5 *M* NaOH (Iyamuremye and Dick, 1996; Phiri et al., 2001).

Although organic amendments cannot usually provide sufficient P for optimum crop productivity because of its low P content, it can increase P availability in high P-fixing soils (Iyamuremye and Dick, 1996; Singh and Jones, 1976). Increases in P availability are usually attributed firstly to an increase in net negative charges on soil colloids that reduce adsorption of applied P (Naidu et al., 1990), and secondly to organic anions formed by decomposing organic manure that can compete with P for the same adsorption sites in the soil (Eastwood and Sartain, 1990; Iyamuremye et al., 1996). The fate and dynamics of dissolved P from applied PR to soils will be greatly influenced by the dynamics of soil organic matter because of its effect on nutrient cycling, soil structure, and biological function of the soil (Brown et al., 1994).

In recent years, considerable emphasis has been given to NCPR because of its high solubility in acid soils (He et al., 1996a, b; Leon et al., 1986; Wright et al., 1992. Information regarding the Syrian PR (SYPR) used in this study is limited to two recent studies in which SYPR was shown to be an effective P fertilizer for rape plants (*Brassica napus* L.) in alkaline soil (pH=7.72; Habib et al., 1999) and in an acidic Lily soil grown maize (pH=3.95; Alloush and Clark, 2001). In this study, I compared the dissolution of NCPR to a PR from Syria (SYPR) in an acidic Lily soil from West Virginia, amended with freshly collected cattle manure in presence and absence of switch grass (*Panicum virgatum*). The overall objectives were to determine: (i) the time course of dissolution of SYPR in acidic soil compared to NCPR; (ii) the effect of organic manure amendment to acidic soil on the dissolution rate of NCPR AND SYPR; (iii) if the measurement of Pi in 0.5 *M* NaOH extractant underestimates the actual dissolution rate of PR; (iv) the effect of plant uptake on the dissolution of NCPR and SYPR; (v) determine the effects of soil amendments with NCPR or SYPR and organic manure on plant uptake efficiency of mineral nutrients that are usually either deficient (P, Ca and Mg) or toxic (Al, Mn and Fe) in acidic soils.

Materials and methods

Soil and amendments

Acidic Lily soil (7%, clay; 31%, silt; 63%, sand; fine loamy, siliceous, mesic, Typic Hapludult) was collected from the 0–50-cm depth near the Appalachian Farming System Research Center, USDA-ARS, Beaver, WV, US. Selected properties of the soil were 4.2 pH in water; 8.9 mg kg^{-1} organic C; 3.7 mg Bray extractable P kg^{-1}; 3.5 mg $NaHCO_3$ extractable P kg^{-1}; 21 and 10 mg kg^{-1} extractable Ca and Mg in 1 *M* NH_4OAc; 60, 34, 88 mg kg^{-1} for Mn, Fe, and Al extractable in 5 m*M* DTPA (Page et al., 1982).

Air-dried soil (sieved <2 mm screen) was amended with 3% air-dry cattle manure (OM) and/or 500 mg P kg^{-1} as North Carolina or Syrian phosphate rock (NCPR, 13.2% P; SYPR, from Ain Lyllon location-friable type, 12.2% P). Cattle manure was collected from a grazed pasture, air-dried, ground and sieved (<1 mm), prior to mixing with the soil. Some properties of the cattle manure are: 7.0 pH_w; 383 g kg^{-1} organic C, 696 mg Bray extractable P kg^{-1}, and 547 mg $NaHCO_3$ extractable P kg^{-1}, 4079 mg kg^{-1} NH_4OAc extractable Ca, acid digestible N, P, and Ca concentrations were 20.1, 8.2, and 12.4 g kg^{-1}, respectively. The amended soil was then moistened to 50% of water-holding capacity and distributed into plastic pots, each pot containing 1.2 kg soil (air-dry base). The pots were divided into two sets, each set containing six treatments and four replicates (Control: no application of manure or PR; OM: soil received application of 3% cattle manure; NCPR: soil received 500mg P kg^{-1} as North Carolina PR; SYPR: soil received 500 mg P kg^{-1} Syrian PR; OMNCPR: soil received both 3% manure and 500 mg P kg^{-1} as North Carolina PR; OMSYPR: soil received both 3% manure and 500 mg P kg^{-1} as Syrian PR). The first set of pots was planted with switch grass (*Panicum virgatum*, var. Cave-in-Rock), while the second set contained treated soils was left unplanted. Both sets of pots were placed in a growth chamber (day/night temperature, 25/18 °C; photoperiod, 16-h light; relative humidity of 60%). The pots were watered daily, using deionized water, to maintain 50% water-holding capacity.

Plant response study

The pots were thinned to 7 plants pot^{-1}, 15 days after planting, and irrigated with a nutrient solution containing $Ca(NO_3)_2$ and K_2SO_4 salts at a rate of 60 mg pot^{-1} of N and K. Similar nutrient amendment was repeated after each cutting date. Plants in each pot were cut 2.5 cm above the soil surface at intervals of 42, 63, 84, 105 and 126 days after planting. Herbage yield was oven-dried at 70 °C for at least 48 h, dry matter yield was recorded and the tissue ground prior to digestion and mineral analysis. Portions of 50 to 100 mg dry matter were weighed into teflon containers. To each container, 1.0 mL 15.8 *M* HNO_3 was added and the teflon container placed in microwave digestion bombs (Parr Instrument Co., Moline, IL)*. The samples were microwaved according to the method of Kingston and Jassie (1988). Digestion solutions were analyzed for mineral elements using inductively-coupled plasma spectroscopy (ICP, Jobin Yvon Emission, Model JY 46P, France).

After the final cutting date (126 days after planting), rhizosphere soil (free of roots segments) was collected and air-dried prior to pH measurement and analysis for P from NaOH, $NaHCO_3$, and Bray-1 extracts (Olsen and Sommers, 1982).

Soil incubation study

At interval of 0, 21, 42, 63, 84, 108, and 126 days, the soil in each pot was thoroughly mixed and subsamples of 25 g was collected, air-dried, and stored in sealed, plastic bags for P analysis.

Soil chemical analyses

Dissolution of NCPR and SYPR was measured by modifying the 0.5 *M* NaOH extraction method of Mackay et al. (1986) and as modified by He et al. (1996a). In this procedure, the P released from PR dissolution is mostly sorbed by sesquioxides, oxides, or precipitated as Fe and Al phosphates in acid soil, where both the sorbed P and newly formed Fe and Al phosphates can be extracted into 0.5 *M* NaOH solution through desorption or solubilization. A recovery curve of added P was determined under the same experimental conditions as the NCPR and SYPR dissolution measurements, except for P addition. This correction overcame the problem of possible $Ca(OH)_2$ precipitation and subsequent sorption of Pi during extraction (He et al., 1996a). This was based on the fact that the chemical behavior of phosphate released from the dissolution of PR is similar to that of water-soluble orthophosphate. A recovery value was determined for a specific soil sample by comparing the residual P concentration in the equilibrium solution. Portions of 1.0 g soil were equilibrated on a shaker with 50 mL of 0.5 *M* NaOH solution containing 0, 25, 50, 100, and 200 μg P as KH_2PO_4, respectively, for 16 h. Samples were filtered through Whatman No. 42 filter paper. Inorganic P (Pi) in NaOH extract was determined colorimetrically by the ascorbic-molybdate method (Olsen and Sommers, 1982). Total P (TP) in the NaOH extracts was determined by the same method, following sulfuric acid-persulfate digestion (EPA, 1971), in which P values represent the sum of organic and inorganic P in both extracts. The light

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Table 1. Recovery (%) of added phosphate (KH_2PO_4) by 0.5 *M* NaOH solution from treated Lily soil with 3% cattle manure (OM) as estimated by ΔPi-NaOH method

	Recovery (%) of added phosphate at different rates			
	25 mg P kg^{-1}	50 mg P kg^{-1}	100 mg P kg^{-1}	200 mg P kg^{-1}
	Pi	Pi	Pi	Pi
		%		
Control	99.4 ± 1.7	96.2 ± 1.4	96.5 ± 0.4	98.7 ± 0.2
OM	99.7 ± 6.9	96.8 ± 5.2	99.2 ± 4.3	100.0 ± 0.2

± are standard errors.

color in NaOH and $NaHCO_3$, resulting from dissolved organic manure, was found not to interfere with the P determinations at 882 nm because of the high solution/soil ratio used during the extraction, and because only a small aliquot was taken for the determination of P. The difference in P levels (ΔP) between NCPR or SYPR treated soil with or without OM application, and the control samples, was used as an estimate of PR dissolution (C treatment is the control for NCPR and SYPR treatments; OM is the control for OM-NCPR and OMSYPR treatments). Percent dissolution of NCPR and SYPR was calculated based on TP and Pi values measured in NaOH extracts.

Calculations and statistical analysis

Specific accumulation rates for macro- and micro-nutrient elements (SAcR, μg nutrient g^{-1} DM d^{-1}) were calculated from cumulative dry matter yield using the equation of Williams (1946) between harvest dates 1 and 5 (42 and 126 days, respectively). These values provide average accumulation rates over 85 days. The SAcR equation is:

$$\text{SAcR} = (\text{N4-N1})/(\text{T4-T1}) \times \text{Ln}(\text{W4/W1})/(\text{W4-W1}), \quad (2)$$

where N4 and N1 are the macro- and micro-nutrient contents of shoots, W4 and W1 are shoot dry matter, and T5 and T1 (d) are dates 5 and 1.

Data were statistically analyzed using general analysis of variance (ANOVA Procedure) for the effect of phosphate rock (PR), Cattle manure (OM) and their combination (PRXOM). Differences among treatments means were compared using probabilities of significant and least significant difference (LSD 0.05) values (SAS Institute, 1999).

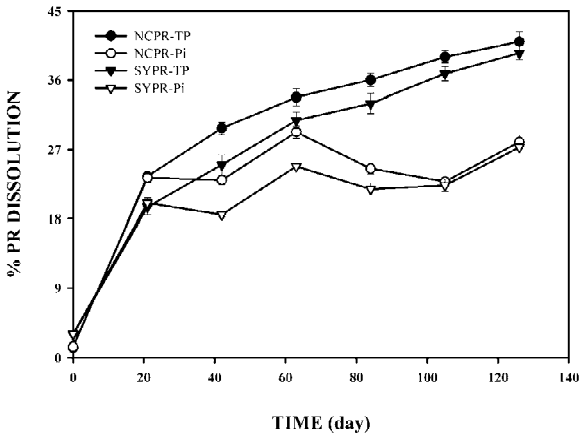

Figure 1. Percent dissolution of North Carolina and Syrian PR (PR; 500 mg P kg^{-1}) in acid Lily soil calculated based on ΔPi and Δ-TP-NaOH method. Bars are standard errors.

Results

Recovery of added P by 0.5 *M* NaOH ranged between 96 and 99.4% for the original soil over the P range applied. OM amendment slightly increased the recovery rates (Table 1) and therefore, NaOH-extractable P from NCPR and SYPR dissolution were not corrected.

PR dissolution and P-availability

As measured by the Δ-TP-NaOH (total P in the NaOH extractant) method, percent dissolution of phosphate rock reached 40 and 41% for NCPR and SYPR, respectively at 126 day (Figure 1). About 20% of both NCPR and SYPR dissolved at 21 days, but subsequent dissolution increasing at a slower rate. NCPR dissolution was slightly higher than dissolution of SYPR by 3% (Figure 1). As determined by the ΔPi-NaOH (inorganic P in NaOH extractant) method, percentage dissolution of applied phosphate rock was about 13% smaller than those calculated based on Δ-TP-

Table 2. Effect of phosphate rock (PR) and cattle manure (OM) amendments on pH, inorganic available P in $NaHCO_3$ and Bray extractions, and extractable Ca in both incubation and switch grass response studies at 126 day

	pH(water)		$NaHCO_3$-Pi (mg kg^{-1})		Bray-Pi (mg kg^{-1})		Extractable Ca (mg kg^{-1})	
	Incubation	Rhizosphere	Incubation	Rhizosphere	Incubation	Rhizosphere	Incubation	Rhizosphere
C	4.2±0.03	4.1±0.04	4.0±0.1	6.2±0.3	3.0±0.1	5.3±0.4	138±0.8	133±2.6
OM	4.7±0.03	4.6±0.11	38.8±1.6	33.0±0.7	58.0±1.5	49.2±1.7	496±17.7	670±102.9
NCPR	4.4±0.03	4.3±0.05	37.8±1.0	37.1±0.5	52.9±1.6	57.6±2.1	731±21.1	571±11.8
SYPR	4.3±0.04	4.2±0.03	37.7±0.5	37.4±0.9	52.1±2.8	60.4±1.9	330±9.6	411±102.2
OMNCPR	5.0±0.01	4.7±0.04	67.7±1.2	66.6±1.1	116.8±1.5	109.3±2.5	726±85.6	910±14.4
OMSYPR	4.9±0.03	4.5±0.02	66.9±0.9	61.6±0.8	110.8±1.3	108.9±3.3	805±3.6	823±18.7
					$P > F$			
PR	***	NS	***	***	***	***	***	***
OM	***	***	***	***	***	***	***	***
PR × OM	*	NS	*	*	*	NS	***	NS

± are standard errors of means.
*, $P \leq= 0.05$; **, $P \leq= 0.01$; ***, $P \leq= 0.001$; NS, not significant.

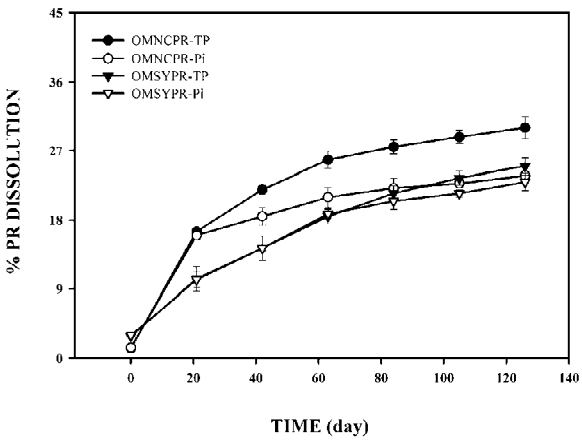

Figure 2. Percent dissolution of North Carolina and Syrian PR (PR; 500 mg P kg^{-1}) in acid Lily soil amended with cattle manure (OM) as calculated based on ΔPi and Δ-TP-NaOH method. Bars are standard errors.

NaOH. Dissolutions of NCPR and SYPR reached 20% by 21 days, and thereafter oscillated by about ± 4%. NCPR and SYPR percentage dissolutions were about 27% after 126 days of incubation. The effect of 3% OM amendment on NCPR and SYPR dissolutions in soil was evident throughout the entire incubation period. Percentage dissolutions were decreased by 11% for NCPR and 14% for SYPR, using Δ-TP-NaOH, and decreased by 4% for both PRs using ΔPi-NaOH (Figure 2). In the OM amended soils, the difference between percentage dissolution, calculated on the basis of Δ-TP and ΔPi-NaOH were 6 and 2% for NCPR and SYPR, respectively.

Amendment of soil with NCPR and SYPR affected ($P < 0.001$) soil pH at 126 days in the incubation study but had no influence on the rhizosphere pH of switch grass (Table 2). OM amendment increased soil pH by about 0.5 of a pH unite in with presence or absence of plants ($P < 0.001$). The increased in pH was greater (1 unit) if combined with application of NCPR or SYPR. In the control treatments, in which no amendment was made, the pH of the soil remained almost unchanged, compared to the starting, 4.2 pH value. Extractable Ca in the original soil was 21 mg kg^{-1} and amendment with NCPR/SYPR ($P < 0.001$) and/or OM ($P < 0.001$) increased extractable Ca in the rhizosphere and incubated soils (Table 2). Extractable Ca increased in incubated soils by 3.6-fold in OM amendment, averaging 4-fold with PR amendment, and 5.6-fold when the soil was amended by both OM and NCPR or SYPR. In the rhizosphere soils, a similar pattern of enhanced extractable Ca was recorded.

The availability of P dissolved from NCPR, SYPR and/or OM was examined by extracting soils from the incubation study and switch grass rhizosphere soils. Available-P was greatly increased in response to amendments of OM ($P < 0.001$), NCPR/SYPR ($P < 0.001$), and their combined application ($P < 0.05$), this was so for both incubated and rhizosphere soils (Table 2). Bicarbonate-Pi in the control incubated soil was very low (4 mg kg^{-1}) and was increased to ∼38 mg kg^{-1} in soil treated with OM, to ∼37 mg kg^{-1} in soil treated with NCPR/SYPR, and even to greater extent (∼67 mg kg^{-1}) when OM and NCPR/SYPR were applied together to the soil.

Table 3. Cumulative dry matter (DM) of switch grass, concentrations of nutrients and trace elements over harvests as affected by cattle manure (OM) or/and NCPR and SYPR amendment to acidic Lily soil

	DM yield	P	Ca	Mg	Al	Mn	Fe
	g pot^{-1}		mg g^{-1} DM			μg g^{-1} DM	
Control	0.1d	0.5d	2.7b	0.6d	34.9a	456.9a	53.0c
OM	17.3ab	1.8c	3.1b	3.6b	12.7cd	208.2b	62.7b
NCPR	13.51b	2.2b	6.8a	2.0c	16.3bc	490.9a	69.0ab
SYPR	9.2c	2.4b	6.7a	1.9c	17.1b	426.9a	69.9a
OMNCPR	18.4a	2.9a	3.6b	4.4a	12.0d	174.3b	67.1ab
OMSYPR	18.7a	2.8a	3.5b	4.2a	12.6cd	180.8b	71.3a
				$P > F$			
PR	***	***	***	***	***	NS	***
OM	***	***	***	***	***	***	NS
PR × OM	***	***	***	NS	***	NS	*

Means followed with the same letter within each column are not significantly different (LSD=0.05). *, $P \geq 0.05$; **, $P \geq 0.01$; ***, $P \geq 0.001$; NS, not significant.

$NaHCO_3$-Pi in rhizosphere soils was slightly lower than those in incubated soils but otherwise showed a similar tend. Bray-Pi values were higher than those of $NaHCO_3$-Pi but showing the same magnitude and trend (Table 2). OM amendment was expected to contribute to available-Pi by 21 and 16 mg kg^{-1} based on calculations using available-Pi in $NaHCO_3$ and Bray extractions of OM used in this experiment.

Growth response and mutrient uptakes

Switch grass grew poorly in acid Lily soil (0.1 g DM pot^{-1}) and exhibited severe symptoms of P, Ca, and mg deficiencies. OM amendment increased significantly ($P < 0.001$) dry matter production (DM) to 17.3 g DM pot^{-1} (Table 3), and even higher when compared to soil amended with NCPR or SYPR alone ($P < 0.001$, 13.5 and 9.2 g DM pot^{-1}). The combination effect of OM and NCPR or SYPR (OMNCPR and OMSYPR treatments) had little effect on DM production over DM production in OM treatment (Table 3).

Concentrations of P, Ca, and Mg were low in the control plants (0.5, 2.7 and 0.6 mg g^{-1}, respectively) and were significantly increased ($P < 0.001$) for soil treated with OM (1.8, 3.1 and 3.6 mg g^{-1}), NCPR (2.2, 6.8 and 2 mg g^{-1}), or SYPR (2.4, 6.7 and 1.9 mg g^{-1}). The combined effect of OM and NCPR/SYPR increased, even to a greater extent, concentrations of P and Mg in DM above those in plants receiving either single amendment of OM, NCPR or SYPR. For Ca, the highest concentrations were with plants receiving NCPR or SYPR amendments (6.8 and 6.7 mg g^{-1}, respectively), and these concentrations were reduced to 3.6 and 3.5 mg g^{-1} if OM was also added to the soil (OMNCPR and OMSYPR treatments). For the micronutrients Al and Mn, soil amendment with OM alone significantly decreased concentrations of Al ($P < 0.001$; from 34.9 in control plants to 12.7 μg g^{-1}), and Mn ($P < 0.001$, from 457 in con-

Table 4. Specific accumulation rate (SAcR) of nutrients and trace elements in dry matter yield over the time between harvest 1 and 5 (42 and 126 days, respectively)

	Nutrients and trace elements SAcR (μg g DM day^{-1})					
	P	Ca	Mg	Al	Mn	Fe
Control	25c	132c	27d	1.7a	23b	2.6d
OM	168b	341b	393b	1.3b	21b	6.4b
NCPR	136b	498a	149c	0.9d	34a	4.6c
SYPR	165b	499a	148c	1.0d	30a	4.6c
OMNCPR	299a	442a	553a	1.3b	20b	8.1a
OMSYPR	298a	467a	569a	1.3b	23b	8.5a
			$P > F$			
PR	***	***	**	**	*	**
OM	***	NS	***	*	***	***
PR × OM	NS	**	NS	***	*	***

Means followed with the same letter within each column are not significantly different (LSD=0.05). *, $P \geq 0.05$; **, $P \geq 0.01$; ***, $P \geq 0.001$; NS, not significant.

trol plants to 208 μg g^{-1}). OM amendment had the reverse effect on Fe concentrations, which increased to 63 μg g^{-1} compared to the control plants (53 μg g^{-1}). Soil amendment with either NCPR or SYPR also decreased Al concentrations in DM, had no effect on Mn, and increased the Fe concentration (Table 3).

Concentrations of nutrients in DM are the function of uptakes and growth rates. Calculations of specific accumulation rates of nutrients in the shoot (SAcR, μg g^{-1} DM day^{-1}) eliminate differences between differently treated plants and estimate the uptake efficiency of mineral nutrients and translocation to the shoots (Table 4). The SAcR of P in the shoots were significantly increased by OM amendment ($P < 0.001$; increase from 24.6 in Control to 168 μg g^{-1} DM day^{-1} in OM treatment), with the increase being even greater if amendment was combined with NCPR or SYPR (299 and 298 μg g^{-1} DM day^{-1}, respectively). SAcRs of P in treatment plants receiving NCPR or SYPR alone were 50% of those receiving both OM and NCPR/SYPR amendments (Table 4). Amendment with OM increased SAcR of Ca, compared to Control, by ~2.7-fold and to a greater extent (~3.8-fold) with NCPR or SYPR. The effect on Mg was more pronounced in which OM increased SAcR values from 27 to 393 μg g^{-1} DM day^{-1} (~14-fold), lesser increase with NCPR/SYPR application (~5.5-folds), and increasing by at least 21-folds when OM and NCPR/SYPR amendment were made together. A reverse trend occurred for Al SAcR values, which were decreased to 1.3 by treating the soil with OM amendment to, and to ~1.0 μg g^{-1} DM day^{-1} by treating the soil with NCPR/SYPR amendment compared to the control 1.7 μ g^{-1} DM day^{-1}. SAcR values for Mn and Fe were increased with NCPR/SYPR amendments and with OM amendment alone in case of Fe only (Table 4). The combined effect of OM and NCPR or SYPR decreased SAcR values for Mn and increased values for Fe. However, there was no significant difference between SAcR for all nutrients in NCPR and SYPR, indicating that both PRs were equally effective in providing nutrient elements for plant uptake.

Effect of plant growth on PR dissolution

The effects of plant uptake, presence of roots, and OM amendment in the dissolution zone on percent dissolutions of NCPR and SYPR are shown in Table 5. Cumulative uptake of P by switch grass was not affected by the source of PR or OM amendment. Dissolved P from NCPR and SYPR were not significantly different in the presence of plant roots, but were significantly different ($P = 0.01$) in the incubation study, in which NCPR dissolved more than SYPR (252 vs. 241 and 182 vs. 149). In addition to plant uptake ranging from 20 to 29 mg pot^{-1}, dissolved P from NCPR and SYPR were higher in the rhizosphere compared to the same treatment in the soil incubation study. These differences are 6 and 8% more dissolved P from NCPR and SYPR, respectively and 6 and 12% more dissolved P for NCPR and SYPR when amendments are combined with application of OM. Percentage dissolution, that takes into consideration plant uptake, were higher in presence of plant roots reaching 53 and 52% for NCPR and SYPR, compared to 42 and 40% from the same treatments in the incubation study. However, in both studies, amendment with OM reduced the percentage dissolution of both NCPR and SYPR ($P < 0.001$) by about ~12–15% (Table 5).

Discussion

Dissolution was similar for NCPR and SYPR in Lily acidic soil. Approximately 40% of both PRs dissolved at 126 day based on the ΔTP-NaOH method (Figure 1). Dissolution was more rapid early but persisted at a decreasing arte throughout the experiment (Figure 1). The dissolution rates of phosphate rock based on ΔTP-NaOH estimation method were higher than those calculated based on ΔPi-NaOH by about 13% at 126 days of incubation. It is also of interest to note that dissolution rates estimated based on ΔPi-NaOH for NCPR and SYPR were oscillating within ±5% throughout the experiment (Figure 1). He et al. (1996a) reported similar dissolution rate for NCPR (30%) in the same acidic Lily soil using the ΔPi-NaOH estimation method but no oscillation was observed. It is therefore a question as to whether dissolution of applied phosphate rock should be estimated by ΔPi-NaOH or by ΔTP-NaOH method? It was estimated for NaOH extraction to include up to 25% of total soil Po (Phiri et al., 2001), which is usually stable and may represent a relatively active pool of P in acid soils under cultivation (Tiessen et al., 1992). The colorimetric determination of Pi by the acid molybdate-ascorbic method, used by most researchers, is expected to overestimate Pi, as was demonstrated for water (Broberg and Pettersson, 1988; Burton, 1973). Measurement of P includes, in addition to Pi, a considerable amount of Po that would be released from organic compounds due to acid hy-

Table 5. Effect of cattle manure and plant growth on plant P uptake and dissolution of NCPR and SYPR in Lily soil as estimated by Δ-TP-NaOH method. Also given general analysis of variance for the effect of PR source and cattle manure on PR dissolution

	Plant pot experiment				Incubation pot experiment		
	P uptake	P dissolution	Total P dissolution	PR dissolution	P dissolution	PR dissolution	Plant effect on PR dissolution
		mg pot^{-1}		%	mg pot^{-1}	%	%
NCPR	29 ± 3.4	287 ± 6.3	316 ± 4.9	53 ± 0.8	252 ± 6.2	42 ± 1.0	11 ± 1.2
SYPR	26 ± 3.0	288 ± 9.8	314 ± 7.8	52 ± 1.3	241 ± 3.0	40 ± 0.5	12 ± 1.0
OMNCPR	25 ± 3.5	218 ± 10.7	243 ± 14.2	41 ± 2.4	182 ± 5.8	30 ± 1.0	11 ± 3.0
OMSYPR	20 ± 1.6	216 ± 5.6	237 ± 4.1	39 ± 0.7	149 ± 6.7	25 ± 1.1	14 ± 1.6
				$P > F$			
PR Source	NS	NS	NS	NS	**	**	NS
OM	NS	***	***	***	***	***	NS

± are standard errors of means.
*, $P \geq 0.05$; **, $P \geq 0.01$; ***, $P \geq 0.001$; NS, not significant.

drolysis of organic compounds (Nash and Halliwell, 1999). The observed oscillation in estimated ΔPi-NaOH could have resulted from the equilibration and turnover of dissolved Pi from NCPR and SYPR into Po fraction of the NaOH extraction.

The effect of OM application on NCPR and SYPR dissolution in soil was evident throughout the entire incubation period. Addition of fresh OM at 3% of the soil mixture decreased both NCPR and SYPR dissolution by about 13% (Figure 2), and there was no oscillation in ΔPi-NaOH values, as was observed in the absence of OM (Figure 1). The reduction in NCPR and SYPR dissolution was probably due to the input of Pi and easily mineralized Po in the added OM in the dissolution zone inhibiting phosphate rock dissolution (Equation. (1)). Organic P in the original soil is probably associated with well-decomposed organic matter, resulting in stable humic compounds (Tiessen et al., 1992), whereas freshly applied OM supplied mostly labile Po-compounds that are easily mineralized (Bowan and Cole, 1978). The OM applied contained considerable amount of extractable Pi and Po compounds decomposable by microorganism (Chauhan et al., 1979) and has a fast turnover to Pi (Haynes and Swift, 1988; Tiessen et al., 1983). This is because the major component of labile Po is a diester PO_4 (Tiessen et al., 1984), which prevents it from binding strongly to soil minerals and makes it susceptible to rapid mineralization (Ghoshal, 1975; Trassar-Cepeda and Carballas, 1991). The availability of Pi as estimated by the Bray No. 1 extraction procedure was higher, compared to values estimated by $NaHCO_3$ (Table 2). Both estimations showed a similar trend in which OM or NCPR/SYPR amendments had similar available-Pi values. OM amendment with either NCPR or SYPR had an even greater available-Pi, compared to any single OM, NCPR or SYPR amendment. However, the availability of Pi from dissolved ΔPi-NaOH from NCPR or SYPR was about ∼29%, and was increased to about ∼45% when OM was also added. These percentages are within the range of 30–50% of dissolved P from PR that remained available for plant uptakes (Bolan and Hedley, 1990; Kanabo and Gilkes, 1987). However, the enhanced available-Pi when OM was also amended with NCPR/SYPR could be attributed to the role of OM in increasing net negative charges in the soil that decreases the adsorption of applied P (Naidu et al., 1990), and to the formation of organic anions, which compete with Pi for the same adsorption sites on soil constituents (Eastwood and Sartain, 1990; Iyamuremye et al., 1996). Therefore, the enhanced growth of switch grass and concentrations of P in DM yield was not surprising (Table 3).

The presence of plant roots depleting the resulting P and Ca in the dissolution zones of both NCPR and SYPR increased the dissolution of these two types of PR by 11–14% (Table 5) due to plant uptake of these mineral nutrient elements. Plant roots took up 8–10% of the total dissolved P. Both NCPR and SYPR were evenly effective in supplying P for adequate maximum plant production (Table 5). Consequently, the growth of switch grass and mineral nutrient concentrations of P, Ca, and mg were enhanced in amended acid Lily soil with NCPR and SYPR compared to the control plants (Table 3). These observations are in accord-

ance with reported data made in the same acid soil for NCPR growing chickpea plants (Alloush et al., 2000) and for SYPR growing maize plants (Alloush and Clark, 2001), and for rape plant grown in alkaline soil amended with SYPR (Habib et al., 1999). The beneficiary effects of applied NCPR and SYPR on growth and P, Ca and Mg uptakes is even greater when OM is also applied to the soil (Table 3). Although plants in all treatments were supplied with equal quantities of mineral N, Ca, Mg and K, differences in growth and mineral concentration were evident among treatments. Therefore, calculation of specific accumulation rates (SAcR, μg g^{-1} DM day^{-1}) of nutrients were calculated using Equation (2) that discard differences between treatment related to plant size and quantities of nutrient uptake. It provides an indication of the efficiency with what plants acquire nutrients from the soil and translocate the elements to the shoots. Amendment with NCPR or SYPR increased SAcR of P over the Control plants by about ~6-fold and by 12-fold when OM was also added to the soil (Table 4). OM amendment to acid soil seems to have also increased the accumulation of Ca and Mg in the shoot DM of switch grass and this effect was even greater for mg if application was combined with NCPR or SYPR (Alloush et al., 2000). This beneficiary effects of OM amendment on enhancing Ca and Mg acquisition was reported for chickpea plants (Alloush et al., 2000) and probably resulted from chelation of Ca^{2+} and Mg^{2+} by organic acids and phenolics compounds derived from decomposing OM (Bolan et al., 1994; Harter and Naidu, 1995; Hue, 1991).

Al, Mn and Fe are readily soluble in acidic soil (Foy, 1992) and plants grown in such soil can have high concentrations of these nutrients and symptoms of toxicity often occurred (Marschner, 1995). The beneficiary effect of OM was also evident for Al and Mn in which concentrations of these nutrients were reduced considerably compared to control plants (Table 3). SAcR values for Al, the major toxic element in acid soils, were reduced by 24% in OM amended plants, and by about ~44% in soil treated with NCPR/SYPR (Table 4). Mechanisms for reduction in acquisition of Al might be associated with inactivation of soluble Al due to enhanced Ca concentrations and increased pH (Table 2) of the soil amended with phosphate rock and possibly by formation of organic metal complexes (Iyamuremye and Dick, 1996). Phenolic acids have particularly been associated with inactivation of Al (Harter and Naidu, 1995). This lead to the conclusion that in acidic soils, amendments, which include application of phosphate rock and OM might be appropriate for alleviating common problems associated with P, Ca and Mg deficiency and Al toxicity of plants grown in acidic soils. These amendments also correct slightly the pH of the soil and considerably correct the fertility status of the soil. This idea seems more feasible in pasture landscape, in which the soil receives a considerable amount of cattle manure deposited by the grazing animals. Sustainable pasture implies the recycling of nutrients (Haynes and Williams, 1993) and thus a continuous transformation and turnover of phosphate rock, a low-cost alternative to manufactured P fertilizer, thus maintaining P in available form for plant uptakes and forage productivity.

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