Existing Versus Added Soil Organic Matter in Relation to Phosphorus Availability on Lateritic Soils

Fadly Hairannoor Yusran[1]

Received 10 October 2006 / Accepted 28 May 2007

ABSTRACT

Existing Versus Added Soil Organic Matter in Relation to Phosphorus Availability on Lateritic Soils (F.H. Yusran): Lateritic soils (Ultisols and Oxisols) are commonly characterised by high phosphate sorbing capacity due to the type of clay and present high content of aluminium (Al) and iron (Fe) oxides. Addition of fresh organic matter (OM) may contribute to management of these soils by releasing more bicarbonate-extractable phosphorus (BP) through organic phosphorus (OP) transformation, or by the soluble component of OM additions desorbing phosphate by ligand exchange. It is not known, however, whether BP results solely from addition of new OM (by either mineralisation or desorption) or from transformation of inherent or pre-existing in soil. We considered that removing the existing soil OM and replacing it with an equivalent amount of new OM may help to resolve this issue, especially with respect to P transformation after OM additions. Three lateritic soils of Western Australia (including a deep regolith material with very low inherent soil OM (SOM)) were used, and sub-samples of the three soils were combusted (450° C) to obtain soils effectively free from existing OM. A further sub-sample of the soils was not combusted. Both soil groups, receiving the same amount of organic carbon (OC, from 80 ton ha^{-1} biomass + soil OM or biomass equal to soil OM) from peat, wheat straw (*Triticum aestivum* L.) and lucerne hay (*Medicago sativa* L.), were incubated for nine months. Soil bicarbonate-extractable P as well as non-extractable P (NP, measured as Total-P (TP)-BP) increased due to new OM application in the order lucerne hay>peat>wheat straw. The correlation between BP with soil organic carbon (SOC) became more positive over time. Microbial biomass phosphorus (MBP) was not well correlated with the increase of NP content and phosphatase was not related to the increase in BP. Overall, freshly applied (new) OM not only contributed to the increased level of P compared with the existing OM treatment.

Keywords: Oxisols, phosphatase, P-mineralisation, soil organic carbon, Ultisols

INTRODUCTION

Organic matter is involved indirectly in many reactions and processes in soils, creating favourable conditions for the availability of nutrients. The decomposition of SOM will produce a pool of OC which is easily mineralised and another pool which is slowly degradable (Eusterhues *et al.*, 2003). This pool is decomposed slowly due to: (i) chemical recalcitrance, *i.e.* stabilisation attributable to the structural properties of the organic matter, (ii) inclusion of OM into aggregates or micropores, leading to physical protection from microbial attack (Strong *et al.*, 1999), and (iii) interaction of carbon compounds with soil minerals (Baldock and Skjemstad, 2000; Sollins *et al.*, 1996).

Plant available phosphate (measured by bicarbonate extraction at pH 8.5) is usually present only in very small amount in Ultisols and Oxisols partly because of its strong adsorption by with Al and Fe (Iyamuremye and Dick, 1996). However, the concentration of organic phosphorus (OP) can reach more that 50% from TP in lateritic or intensely weathered soils (Beck and Sanchez, 1994; Chepkwony *et al.*, 2001) as highly charged monoester-P allows rapid adsorption on soil minerals and extensive interaction with sesquioxides which protect inositol phosphate from degradation (Turrion *et al.*, 2001). Hence, any mechanism that can ensure the continuity of OP to inorganic-P (IP) transformation after fresh OM addition may become important in lateritic soils.

The effect of recently added OM needs to be distinguished from the effect of inherent SOM. The stable and inert pools of OM in soil can be very old, ranging from hundred to thousand years

---

[1] Soil Department, Faculty of Agriculture, Lambung Mangkurat University, Banjarbaru 70714
Kalimantan Selatan. e-mail: fhyusran@unlam.ac.id
J. Tanah Trop., Vol. 13, No. 1, 2008: 23-34
ISSN 0852-257X

(Eusterhues *et al.*, 2003; Falloon and Smith, 1998; Hassink, 1997; Monreal *et al.*, 1997; Oades, 1995 and their identity, as well as their physical and chemical properties, are not well understood (Eusterhues *et al.*, 2003; Hsieh, 1992; Ruhlmann, 1999; Theng *et al.*, 1992). In order to study the effect of adding OM to soil in terms of phosphate adsorption, it would be useful to remove the stable pools of SOM from soil samples so that the effect of newly added OM does not interact with that of stable pools.

The objectives of this study were therefore: (1) to study the contribution of newly applied OM on different forms of P in soil such as BP, TP, NP, and microbial biomass-P (MBP), (2) to measure if MBP and/or SOC generate more P in low P environment indicated by their positive relationship with BP, and (3) to measure whether phosphatase becomes more active in mediating the transformation of OP to IP in totally newly added OM indicated by positive correlation between BP and phosphatase activity.

MATERIALS AND METHODS

This incubation experiment was set up in a factorial design using completely randomized blocks. The treatments are presented in Table 1 with chemical characteristics (C, N, and P contents) of the treatments in Table 2.

The treatments with new SOM were based on the OC concentration in peat, wheat straw, and lucerne hay plus OC concentration in the existing SOM in the original soil samples. In the experimental design, for any given OM source (new and/or existing), the concentrations of OC was similar.

Procedures

An Ultisol (Typic kandiudult) was collected near Jarrahdale (Latitude 33°19'40" S; Longitude 115°45'55" E) and an Oxisol (Plinthic eutrodox) near Bunbury (Latitude 32°19'00" S; Longitude 116°11'00" E) in Western Australia. Both soils were selected due to their high content of extractable-Al and Fe (McArthur, 1991) and in order to see their effects on phosphate adsorption and P mobility in the soils. The third soil (subsurface) was a deep regolith material collected at Boddington Gold mine in Western Australia where the soils have considerable extractable-Al and Fe but had very low SOM. This soil is developed from deep chemical weathering of Archaean granites and migmatites. The subsurface soil was selected to isolate the effect of combustion on soil physical and chemical characteristics, since the amount of soil organic matter was negligible (Table 3)

Addition of soil starter (one gram of original soil similar to the soils used for incubation) after combustion was assumed that living soil microbes (if any) would return to normal condition as before the combustion. Soils (including the Ultisols from Jarrahdale) in this area are classified as Darling Range laterites, which have very low concentrations of nutrients (Gilkes *et al.*, 1973; McArthur, 1991). Topsoil commonly has a coarse texture with 50-82% gravel (3-8 mm) and pH slightly acidic (5.5-6.5) (McArthur, 1991). Selected characteristics of soils are presented in Table 4.

Peat, wheat straw, and lucerne hay were oven-dried (60°C) for two days, and chopped with a grinding mill (*RetschMühle*). They were ground with another mill (C and N Junior, ≤ 1 mm sieve) for more rapid decomposition.

Soil samples from the field were air-dried and sieved with ≥ 2 mm sieve. For the newly added OM treatments, soils were combusted at 450°C for 12 hours using a pottery kiln (Kiln West, model 6191Z). Soil samples were put into three separate steel containers having dimension of 35 cm x35 cm x15 cm each. Each container had a loosely fitting lid, allowing fumes from combustion of samples to be released easily. Soil was combusted until the colours become lighter than the original and the OC content about 0.00%. A temperature of 450°C is hot enough to deplete OC content, but has been found in some previous works to have a minimal effect on other physical and chemical properties of soils such as porosity, textural class, and soil acidity (Giovannini *et al.*, 1988; Kang and Sajjapongse, 1980).

Treatments were applied together with a 'soil starter' as an inoculant to introduce new decomposer micro-organisms. The 'soil starter' was one gram of original soil similar to the soils used for incubation. Soil (0.5 kg) was weighed for each pot and OM treatments were applied by homogeneously mixing the soil and the respective treatments with mechanical mixer (100 times, end-over end). Soils were incubated for three months to allow decomposition before the first sampling. Water was added weekly to reach a moisture content equivalent to 60% of the maximum water holding capacity of the soil, determined by weighing. Soil characteristics before treatment (physical, chemical, and biological) were analysed for comparison with the same parameters during the course of incubation. Monocalcium phosphate was added (45.8 mg kg^{-1}) to equilibrate in term of precipitation reactions with exchangeable-Al and Fe, and chemisorption to clay and sesquioxide minerals, in soils for a one-month period prior to OM treatments. The amount of monocalcium phosphate was equal to 100 kg ha^{-1} triple superphosphate (TSP), recommended P fertiliser for lateritic soil in Indonesia (Suhadi, 2002). This additional P was added to ensure that P content adsorbed to soil particles and Al- and Fe-oxide was high enough to see the effect of organic matter addition on phosphate release.

The statistical significance of treatment, interaction effects, correlation and regressions were carried out using GenStat (Payne *et al.*, 1987) and SPSS (Coakes, 2001).

Parameters were measured at three sampling times, *i.e.* three, six, and nine months after SOM treatments. Part of the sample was kept fresh in a 150 mL plastic (tight-capped) bottle for ammonium and nitrate analyses the following day. Samples for these analyses were kept overnight in cool storage. The rest of the samples were air dried and sieved (≤ 2 mm) and kept in sealed plastic bags for other chemical analyses.

Measurements

The principle of dissolved organic-C (DOC) was from the method of (Wagai and Sollins, 2002). Total-P was measured in acid-persulfate (Nelson, 1987). Total converted phosphate in extract was measured colorimetrically as described by Rayment and Higginson (1992). Bicarbonate-P (BP) was extracted using 0.5 M $NaHCO_3$ pH 8.5. This is a modification from a method by Olsen *et al.* (1954) described by Rayment and Higginson (1992). The manual colorimetric for determination of phosphate in the extract was based on the method of Murphy and Riley (1962). Measurement of non-extractable-P (NP) was conducted by measuring TP with acid-persulfate digestion (Nelson, 1987) and then subtracting the results with the BP content of the same soil calculated beforehand. Acid phosphatase (phosphomonoesterase EC 3.1.3.2) activity was determined on a one gram soil sample according to the method of Tabatabai (1994). Microbial biomass-P (MBP) was determined by the method of Wu *et al.* (2000) following the fumigation and extraction method of Powlson and Jenkinson (1976). Aluminium and Fe oxides were calculated from acid oxalate extraction as explained by Rayment and Higginson (1992). Soil water content was measured exactly one week after pot watering.

Table 1. Organic matter sources (peat, wheat straw, and lucerne hay) used as treatments in the experiment.

Type of Soil Organic Matter	Source
Existing	Peat (OC in 80 ton ha^{-1} peat + OC in existing SOM) Wheat straw (OC in 80 ton ha^{-1} wheat straw + OC in existing SOM Lucerne hay (OC in 80 ton ha^{-1} lucerne hay + OC in existing SOM)
New	Peat (OC in 80 ton ha^{-1} peat + OC in additional peat equal to that of pre-existing SOM) Wheat straw (OC in 80 ton ha^{-1} wheat straw + OC in additional wheat straw equal that of pre-existing SOM) Lucerne hay (OC in 80 ton ha^{-1} lucerne hay + OC in additional lucerne hay equal to that of pre-existing SOM)

Table 2. Some chemical characteristics of organic matter sources for treatments.

Source of Carbon	Total-N (g kg^{-1})	Total-C (%)	C/N ratio	Total-P (%)
Peat	5.6	31.5	56	0.16
Wheat straw	7.6	43.4	57	0.20
Lucerne hay	26.9	41.4	15	0.25

Table 3. Characteristics of soils (subsurface, Ultisols, and Oxisols) used in the glasshouse incubation.

Soil Characteristics	Soil		
	Subsurface Regolith 'Soil'	Ultisols (Typic Kandiudult)	Oxisols (Plinthic Eutrodox)
[1]Texture:			
Sand (%)	48	89	60
Silt (%)	45	5	9
Clay (%)	7	6	31
[2]DOC (mg kg^{-1})	3 ± 0.8	30 ± 3.0	13 ± 3.1
[3]Org-C (g kg^{-1})	0.35	58	28
[3]Total-N (g kg^{-1})	0.29	2.0	1.5
[4]Total-P (mg kg^{-1})	237 ± 5.5	57 ± 3.2	83 ± 6.7
[5]Bicarb. P (mg kg^{-1})	26 ± 2.1	7 ± 0.9	8 ± 1.2
[5]Ext-K (mg kg^{-1})	37	174	37
[6]Exch. cat. ($cmol^+$ kg^{-1})			
CEC	2.1	2.8	7.2
Ca	0.8	1.2	1.8
Mg	1.2	0.8	3.0
K	0.1	0.1	0.3
Na	1.1	0.9	1.0
pH (1:5 soil:H_2O)	6.8 ± 0.06	6.2 ± 0.12	6.2 ± 0.20
[7]Oxalate-Al (g kg^{-1})	1.0 ± 0.19	11.0 ± 1.0	11.0 ± 2.0
[7]Oxalate-Fe (g kg^{-1})	18.0 ± 1.0	73.0 ± 3.0	274.0 ± 7.0

Notes: [1]Pipette method, [2]TOC in water extract, [3]Leco C and N analyser, [4]Persulfate digestion, [5]Bicarbonate extraction, [6]Silver thiourea, [7]Ammonium oxalate extraction. Values after ± are standard errors.

Table 4. Some characteristics of soil samples before and after combustion.

Characteristics	Soil					
	Subsurface 'Regolith' Soil		Ultisols (Typic kandiudult)		Oxisols (Plinthic eutrodox)	
	Before	After	Before	After	Before	After
Org-C (g kg^{-1})	0.4	0.1	58.1	0.2	28.5	0.0
Total-N (g kg^{-1})	0.3	0.1	2.0	0.1	1.5	0.0
Total-P[1] (mg kg^{-1})	237±6	244±4	57±3.2	69±5.5	83±6.7	89±2
Ext-Al (mg kg^{-1})	1±0.2	10±1.4	11±1.3	28±3.5	11±1.8	43±5.1
Ext-Fe (mg kg^{-1})	18±0.9	47±1.8	73±2.8	182±4.6	247±7.0	260±7.36
pH	6.8±0.06	6.5±0.16	6.2±0.12	7.1±0.13	6.2±0.20	6.0±0.04

Note: [1] = Persulfate digest method

RESULTS AND DISCUSSION

The new OM treatment had significantly increased BP concentrations (Figure 1) compared with existing OM treatments, especially in the Ultisol (*ca.* 150% increase) and the Oxisol (*ca.* 130% increase). In the case of the subsurface soil, P immobilisation is likely to have been taking place after lucerne hay addition, indicated by higher MBP in the first six months of incubation (Figure 2). The higher BP content in subsurface soil (Table 4) has probably allowed the population of soil micro-organisms to increase faster than Ultisol and Oxisol, even in combusted soil samples, causing immobilisation of P. Although P immobilisation can persist longer due to green manure addition (Costa, 2000), the results in this experiment showed that at the end of the incubation, this P immobilisation had declined indicated by smaller MBP (Figure 2).

The increase of TP allows two interpretations. First, additional OM to replace the existing SOM contributed to the increase. The increase in the Ultisol treated with lucerne hay, however, was too high (90%) compared with the P content calculated from the P content of lucerne hay (0.25% P; 41.3%

high (90%) compared with the P content calculated from the P content of lucerne hay (0.25% P; 41.3% C; Table 2). Second, the possibility of mineralisation or solubilisation of occluded P and stabilised source of P in the existing SOM or in inorganic forms pre-existing in the soil (Giardina *et al.*, 2000; Serrasolsas and Khanna, 1995) which can not be extracted with TP procedures by Nelson (1987). This occluded and stabilised source of P might also be derived from monocalcium phosphate added one month before the experimental treatments. Higher TP in subsurface soil where OC content was negligible (Table 4) and lower TP in soils with higher OC (Ultisol and Oxisol) were the indication of this pool of P. However, as soon as the existing SOM was removed by combustion, P was more readily extracted. Alternately, the increase in soil pH, extractable-Al, and extractable-Fe in the Ultisol might have been from the precipitation of Al and Fe-phosphate, or even Ca-phosphate (Giardina *et al.*, 2000; Olsen and Sommers, 1982) after combustion and/or new SOM treatment. In TP extraction process, Al and Fe-phosphate are soluble in alkaline extractants such as $NaHCO_3$ and Ca-phosphate is soluble in acid extractants such as H_2SO_4-$K_2S_2O_8$ (Bhadoria *et al.*, 2002) to increase the concentration of extractable Al and Fe. Both acid extractants were used in TP analysis.

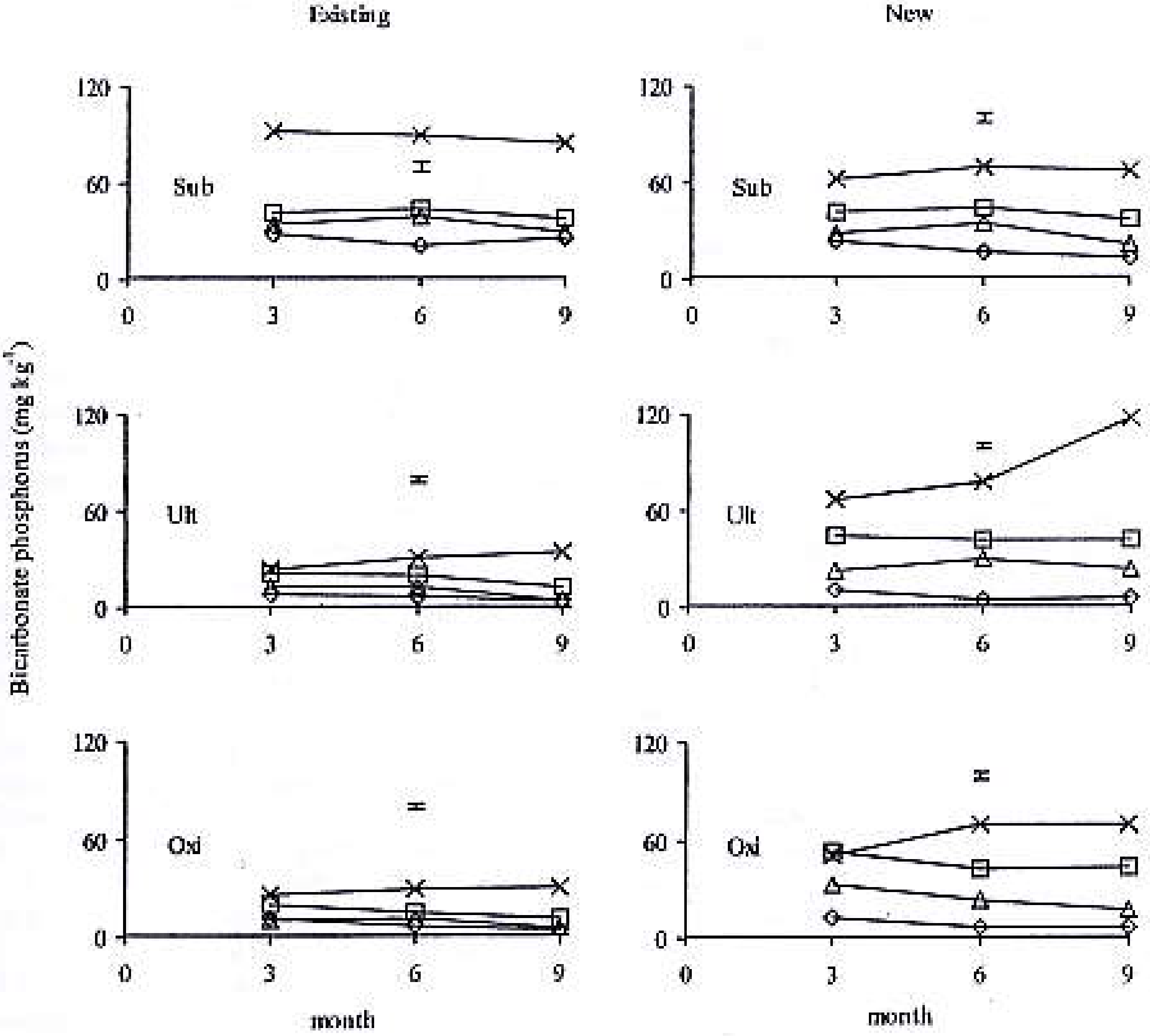

Figure 1. Interaction effect of organic matter sources, type of organic matter, and incubation on bicarbonate phosphorus. ◇ = control, □ = peat, △ = wheat straw, and × = lucerne hay. Sub = Subsoil, Ult = Ultisols, and Oxi = Oxisols. Bar in each graph indicates LSD 5% for organic matter source in every graph.

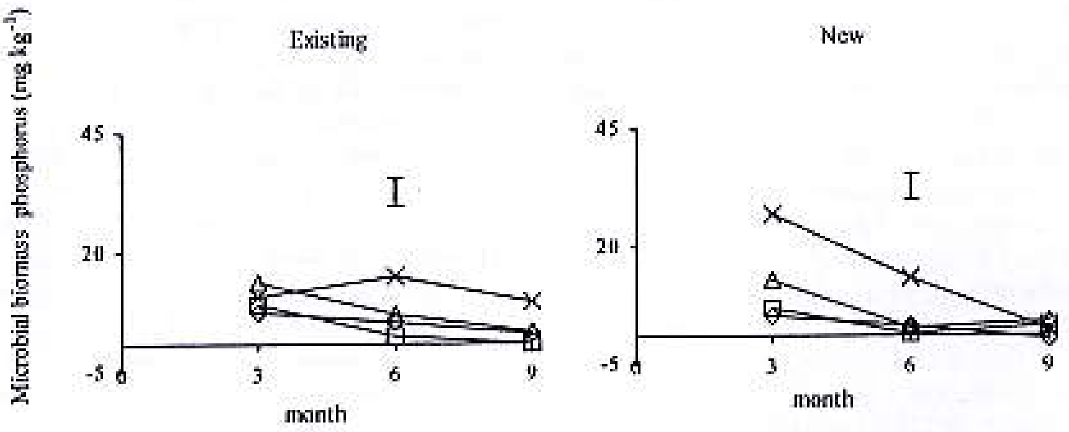

Figure 2. The effect of organic matter sources, type of organic matter, and incubation on microbial biomass phosphorus in subsurface soil. ◇ = control, □ = peat, △= wheat straw, and × = lucerne hay. Bar in each graph indicates LSD 5% for organic matter source in every graph.

As TP content increased with the new OM treatment, consequently, NP content in soils increased. The fact that peat produced more NP in soils than wheat straw treatment was unexpected, since the TP content in wheat straw biomass was higher than that of peat (Table 3). Different type of NP as products of decomposition of peat and wheat straw could be responsible for the result, as peat has more phosphate diesters and other forms of P, including IP (Bedrock *et al.*, 1994).

Closer inspection of results obtained for subsurface soil indicated that the lower concentration of BP in new SOM treatment can be assumed to be due to the heating process imposed on soil samples. The original SOM content in subsurface soil was negligible at 0.04% and the combustion of the soil increased extractable-Al and Fe content (Table 4). The increased reactive Al and Fe would be expected to increase phosphate adsorption capacity (Iyamuremye and Dick, 1996; Zoysa *et al.*, 1999) which may indicated by the lower BP in samples with new SOM treatment (Figure 1). However, for the other soils (the Ultisol and the Oxisols), a decrease in BP was not observed, even though it might be reasonable to assume a similar increase in phosphate adsorption capacity. The increases in extractable-Al and Fe from the burning process occurred together with increased BP concentration in the Ultisol and the Oxisol. This could be due to process related to mineralisation of OM or desorption process but not related to heating process as that of subsurface soil. Therefore, the experiment could not distinguish mineralisation from desorption, but the effect of combustion on phosphate adsorption can probably be neglected. In line with this finding, increased concentration of extractable-P have also observed by several authors, if soils were treated by combustion (Condron *et al.*, 1990), especially in highly weathered soils. This phenomenon was probably due to incomplete oxidation of OP during combustion and the changes in acid solubility of soil IP as a result of combustion (Condron *et al.*, 1990; Williams *et al.*, 1970). Condron *et al.* (1990) even concluded that these potential errors have to be avoided if dealing with OP in strongly weathered soil samples. However, since subsurface soil did not show the increase in either TP or NP due to new OM applications (combustion procedure as well), it can be assumed that two mechanisms might not have occurred. Unfortunately, there was no data to support such claim in this experiment.

The Ultisol was the most responsive to OM applications by giving a greater percentage in increase in NP due to newly-added OM, compared with increases in the subsurface soil and the Oxisol. Higher O_2 supply due to sandy texture of the soil (Table 4) possibly enhanced mineralisation processes in the Ultisol. However, the nature of the increase in NP content was not in the form of MBP as predicted beforehand. The positive correlation between NP and MBP at three- and six-month incubation was not observed at nine-month incubation (Table 5). Besides, new OM application decreased MBP in the soil. These observations suggest that the increase of NP may develop from

Table 5. Correlation matrices on all soil parameters. Presented according to incubation times. Only significant correlations are presented. * represents a significant ($p \le 0.05$) and ** a highly significant ($p \le 0.01$) correlation.

Parameter	Parameter									
	TP	NP	BP	Phosphatase	MBP	DOC	MC	Al	Fe	pH
Three-month incubation										
TP										
NP	0.98**									
BP	0.76**	0.63**								
Phosphatase	-0.36**	-0.37**								
MBP	0.38**	0.37**	0.31**							
DOC	0.42**	0.37**	0.47**		0.73**					
MC	0.28*	0.27*	0.25*	0.39**	0.34**	0.34**				
Al (oxalate)	-0.35**	-0.39**		-0.32**						
Fe (oxalate)	-0.48**	-0.50**	-0.25*	-0.36**			0.43**	0.54**		
pH										
Six-month incubation										
TP										
NP	0.98**									
BP	0.84**	0.73**								
Phosphatase	0.23*	-0.28*								
MBP	0.38**	0.35**	0.40**							
DOC	0.51**	0.44**	0.61**		0.44**					
MC			0.30*	0.62**	0.25*	0.44**				
Al (oxalate)	-0.30**	-0.34**								
Fe (oxalate)	-0.50**	-0.53**	-0.28*	0.67**		0.37**	0.35**	0.58**		
pH			0.25*		0.31**	0.56**				
Nine-month incubation										
TP										
NP	0.97**									
BP	0.79**	0.62**								
Phosphatase	-0.31**	-0.43**								
MBP			-0.50**							
DOC	0.47**	0.32**	0.70**	0.26**	-0.41**					
MC				0.57**		0.31**				
Al (oxalate)	-0.27**	-0.34**			-0.33**					
Fe (oxalate)	-0.40**	-0.46**		0.44**		0.26*	0.41**	0.63**		
pH	0.26*		0.44**		-0.39**	0.64**			-0.39**	

Notes: TP = Total Phosphorus, NP = Non-extractable Phosphorus, BP = Bicarbonate Phosphorus, MBP = Microbial Biomass Phosphorus, DOC = Dissolved Organic Carbon.

processes other than direct addition of OP from OM biomass such as mineralisation or some other unknown process. All newly applied OM decreased NP relative to TP, but increased the proportion of BP relative to TP. In other words, newly applied OM not only increased NP but might also have released more BP from OP-IP transformation, despite the observation that the treatment itself had created more BP.

In accordance with the increase in NP content, a negative correlation between NP and sesquioxides of Al and Fe (oxalate-extractable) was observed. The higher the NP content, the lower the Al and Fe concentration. As OM could increase NP due to direct effect of OM addition and mineralisation, the treatments could precipitate Al and Fe-oxides (Hue, 1992; Iyamuremye and Dick, 1996). Moreover, the formation of complexes between Al and Fe and humic substances (McCracken *et al.*, 2002; Yang *et al.*, 2001) may have taken place during the experiment, making Al and Fe concentrations decline in soil solution. Since acid ammonium oxalate also effectively extracts Al and Fe from OM (McKeague and Schuppli, 1985; Rayment and Higginson, 1992), therefore, the precipitation of Al and Fe must have been occurred in the experiment.

If we follow the incubation process, BP content was positively correlated with DOC content and the relationship was stronger at higher incubation times, indicated by increasing r values from three- to nine-month incubation. At the same time, BP was negatively correlated with extractable-Fe from three to six months incubation. These observations lead to the deduction that DOC played a positive role in releasing BP to the soil solution. Moreover, as the positive correlation between DOC and NP was steady over time and so was NP and BP, suggested that the increase of BP content in soil solution was more likely to have been a contribution from DOC than from these other factors.

Three months after OM was applied into the soil, mineralisation processes were occurring, indicated by the increased concentrations of DOC, BP, and higher phosphatase activity compared with control soils. At the same time, organic complexes were likely to have been formed with Fe^{3+} and precipitated as insoluble $Fe(OH)_3$ (Hue, 1992; Iyamuremye and Dick, 1996). Another possible mechanism is from soluble humic molecules and low molecular weight aliphatic organic acids from added OM, which can adsorb to the surface of Al and Fe-oxides and block phosphate adsorption site, thus increasing soluble phosphate concentration (Haynes and Mokolobate, 2001). A similar process of phosphate adsorption sites blocking was also observed as higher C content OM such as lucerne hay and wheat straw (Table 2) significantly ($p \leq 0.001$) decreased extractable-Al (data not presented). The same applications, lucerne hay and wheat straw treatments, significantly ($p \leq 0.001$) increased BP (Table 1). However, no correlation between extractable-Al with bicarbonate-P might lead to estimation that the process occurred and equilibrated before the first sampling due to lower initial content of soil extractable-Al than extractable-Fe (Table 3).

The correlation of extractable phosphate with soil pH was explained by assuming that a pH increase due to OM addition (data not presented) would also favour dissolution of SOC (Beck *et al.*, 1999), and thus increase DOC in soils (Figure 3). The increase in pH was probably caused by the oxidation of organic acid anions (*e.g.* oxalate, malate, and citrate) from organic residues that consumed H^+ and released OH^- (Noble *et al.*, 1996; Tang *et al.*, 1999), or from decarboxylation of those anions which consumed protons, released CO_2, and led to a liming effect (Haynes and Mokolobate, 2001; Tang *et al.*, 1999).

In the case of phosphatase, despite the application of OM, as either peat, wheat straw, or lucerne hay increased phosphatase activity, there was no correlation between phosphatase and BP during the experiment. Phosphatase may have been at steady-state, whilst BP could have been continuously released or reach nearly steady-state as well. Such a situation would not lead to a correlation even though a causative effect existed. It is also possible that phosphatase may pre-exist in soil and persist for a long time. In addition, phosphatase activity is subject to end-product suppression by high levels of extractable-P (Allison and Vitousek, 2005; Feng and Xiong, 2002) and phosphatase is not the only enzyme involved in soil P transformation. At least in this experiment, phosphatase activity was not a reliable parameter to estimate P extractability. Therefore, the last hypothesis is only partly supported by the experiment. According to McCallister *et al.* (2002) even though phosphatase was positively correlated with BP, it could not be used to predict P supply to plants nor could it be used as an estimate for the differences of P concentration in plant tissues (Andrade *et al.*, 2001).

Despite the fresh supply of SOC from new OM, micro-organisms producing the phosphatase enzyme were not active enough to make similar phosphatase activity to that observed for the soils with the existing SOM. The trend of increasing phosphatase activity in samples treated with new OM was similar to samples with existing SOM. The magnitude of increase for new OM was around half to that of samples with existing SOM only, especially in the Ultisol (Figure 2). Therefore, it is not high enough to transform NP to BP as indicated by the lack of correlation between phosphatase activity and BP or there was insufficient accessibility of OP to phosphatases. Another explanation for this was the effect of soil combustion on phosphatase. Although phosphatase is resistant to microwave irradiation (Speir *et al.*, 1986), its activity is heat-sensitive (Gosewinkel and Broadbent, 1986). It would be very unlikely if phosphatase or microbial biomass would have survived the high temperature during the combustion period. In addition, the soil starter may have had insufficient microbial population to produce significant amounts of phosphatase.

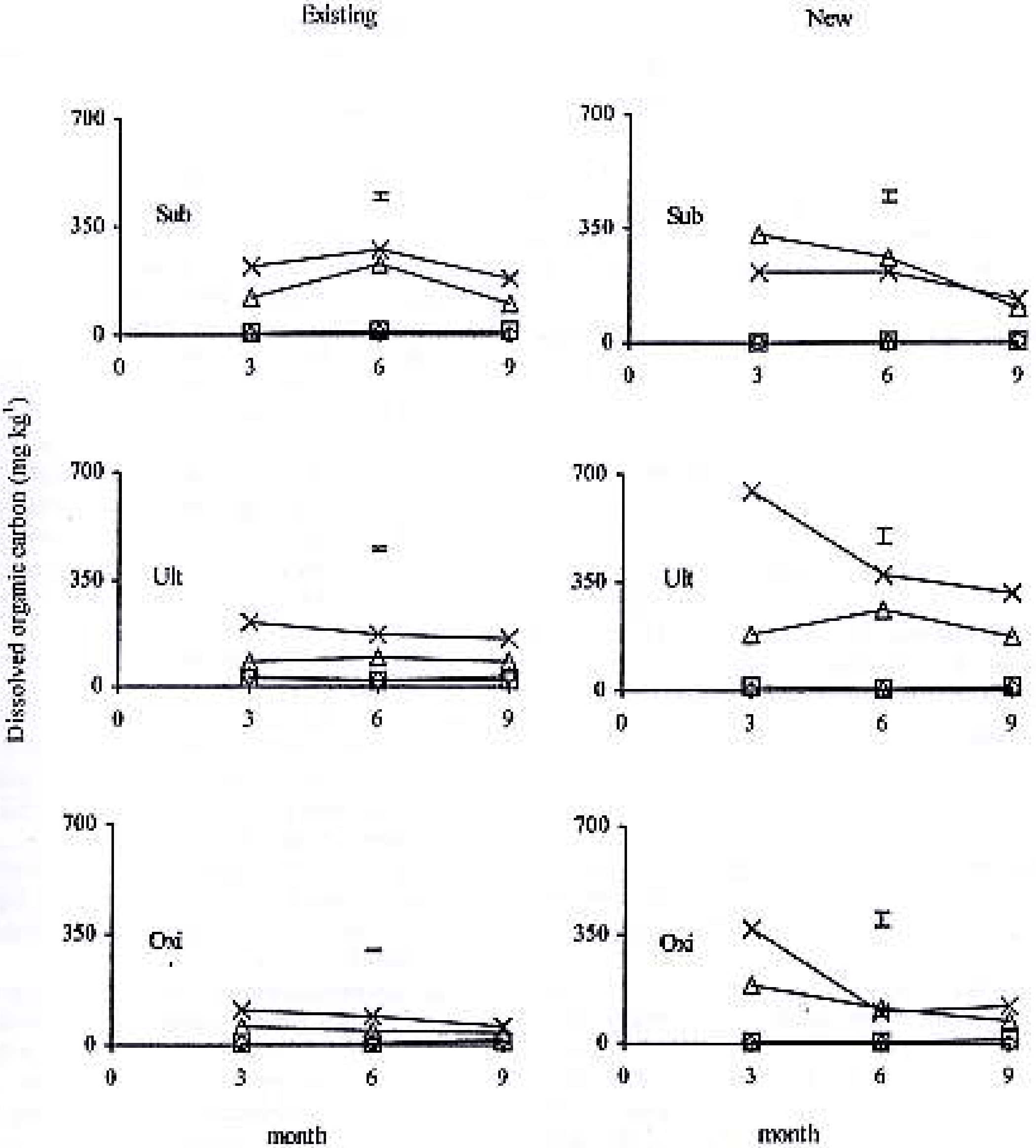

Figure 3. Interaction effect of organic matter sources, type of organic matter, and incubation on dissolved organic carbon. ◇ = control, □ = peat, △ = wheat straw, and × = lucerne hay. Sub = Subsoil, Ult = Ultisol, and Oxi = Oxisol. Bar in each graph indicates LSD 5%.

CONCLUSIONS

Bicarbonate-extractable P increased in soil with applied OM (peat, wheat straw, and lucerne hay) in which the existing SOM had been removed to a greater extent than in soils with existing SOM. The Ultisol had a larger increase in BP than the Oxisol. The addition of OM increased NP concentrations up to six-month incubation. Transformation of NP to extractable phosphate must have been at its maximum around this time indicated by NP decreases as well as increases in BP.

Stronger correlation over time between DOC and BP indicated the importance of DOC in generating BP that could be from OP hydrolysis, transformation, or displacement of adsorbed BP by soluble organic compounds. Contrary to the initial hypothesis, there was only weak evidence that MBP played a role in providing more BP content, as well as phosphatase. Other mechanisms, either chemical or biologically, might have been involved in the process.

To sum, newly applied organic amendment was more effective in releasing available P compared with the pre-existing SOM. However, in order to utilise other pools of P, the increased proportions of NP to TP need to be resolved or analysed further, especially in lateritic soils.

ACKNOWLEDGEMENTS

This research was supported by an ADS (Australian Development Scholarship) funded by AusAID. Supervision and guidance from Andrew W. Rate and Lyn K. Abbott are greatly appreciated.

REFERENCES

Allison, S.D. and P.M. Vitousek. 2005. Responses of extracellular enzymes to simple and complex nutrient inputs. Soil Biol. and Biochem. 37:937-944.

Andrade, L.R.M.D., A.M.D. Carvalho, I.D.C. Mendes, L. Vivaldi, C.T. Karia, and N.T.V. Junqueira. 2001. Effects of cover crops species on Passiflora edulis nutrition. In: W. J. Horst *et al.* (Eds), Plant Nutrition: Food Security and Sustainability of Agro Ecosystems through Basic and Applied Research. Fourteenth International Plant Nutrition Colloquium, Hannover, Germany. Kluwer Academic Publishers, Dordrecht, Netherlands.

Baldock, J.A. and J.O. Skjemstad. 2000. Role of mineral matrix and minerals in protecting natural organic materials against decomposition. Organic Geochemistry, 31: 697-710.

Beck, M.A. and P.A. Sanchez. 1994. Soil phosphorus fraction dynamics during 18 years of cultivation on a Typic Paleudult. Soil Sci. Soc. Am. J., 58: 1424-1431.

Beck, M.A., W.P. Robarge, and S.W. Buol. 1999. Phosphorus retention and release of anions and organic carbon by two Andisols. Eur. J. Soil Sci., 50:157-164.

Bedrock, C.N., M.V. Cheshire, J.A. Chudek, B.A. Goodman, and C.A. Shand. 1994. Use of 31P-NMR to study the forms of phosphorus in peat soils. Science of the Total Environment, 152:1-8.

Bhadoria, P.S., B. Steingrobe, N. Claassen, and H. Liebersbach. 2002. Phosphorus efficiency of wheat and sugar beet seedlings grown in soils with mainly calcium, or iron and aluminium phosphate. Plant and Soil, 246: 41-52.

Chepkwony, C.K., R.J. Haynes, R.S. Swift, and R. Harrison. 2001. Mineralization of soil organic P induced by drying and rewetting as a source of plant-available P in limed and unlimed samples of an acid soil. Plant and Soil, 234: 83-90.

Coakes, S.J. 2001. SPSS: Analysis without Anguish. John Wiley and Sons, Brisbane.

Condron, L.M., J.O. Moir, H. Tiessen, and J.W.B. Stewart. 1990. Critical evaluation of methods for determining total organic phosphorus in tropical soils. Soil Sci. Soc. Am. J., 54: 1261-1266.

Costa, W.A.J.M.D. 2000. Decomposition and nutrient release from green manures of different tree species in three agroecological zones of Sri Lanka. In: H. P. M. Gunasena (Ed). Eleventh National Workshop on Multipurpose Trees, Kandy, Sri Lanka. Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka, pp 1-34.

Eusterhues, K., C. Rumpel, M. Kleber, and I. Kogel-Knabner. 2003. Stabilization of soil organic matter by interactions with minerals as revealed by mineral dissolution and oxidative degradation. Organic Geochemistry, 34: 1591-1600.

Falloon, P. and P. Smith. 1998. The role of refractory soil organic matter in soil organic matter models. Mitteilungen der Deutschen Bodenkundlichen Gesellschaft, 87: 253-264.

Feng, G. and L. Xiong. 2002. Exploring plant factors for increasing phosphorus utilization from rock phosphates and native soil phosphates in acidic soils. International Conference on Isotopic and Nuclear Analytical Techniques for Health and Environment, Vienna, Austria.

Giardina, C.P., R.L. Sanford, Jr., and I.C. Dockersmith. 2000. Changes in soil phosphorus and nitrogen during slash-and-burn clearing of a dry tropical forest. Soil Sci. Soc. Am. J, 64: 399-405.

Gilkes, R.J., G. Scholz, and G.M. Dimmock. 1973. Lateritic deep weathering of granite. J.Soil Sci., 24: 523-536.

Giovannini, G., S. Lucchesi, and M. Giachetti. 1988. Effect of heating on some physical and chemical parameters related to soil aggregation and erodibility. Soil Sci., 146: 255-261.

Gosewinkel, U. and F.E. Broadbent. 1986. Decomposition of phosphatase from extracted soil humic substances with electron donating reagents. Soil Sci, 141: 261-267.

Hassink, J. 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant and Soil, 191: 77-87.

Haynes, R.J. and M.S. Mokolobate. 2001. Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved. Nutrient Cycling in Agroecosystems, 59: 47-63.

Hsieh, Y.P. 1992. Pool size and mean age of stable soil organic carbon in cropland. Soil Sci. Soc. Am. J, 56: 460-464.

Hue, N.V. 1992. Correcting soil acidity of highly weathered ultisol with chicken manure and sewage sludge. Comm. Soil Sci. Plant Anal., 23: 241-264.

Iyamuremye, F. and R.P. Dick. 1996. Organic amendments and phosphorus sorption by soils. Adv. Agron, 56: 139-185.

Kang, B.T. and A. Sajjapongse. 1980. Effect of heating on properties of some soils from southern Nigeria and growth of rice. Plant and Soil, 55: 85-95.

Linquist, B.A., P.W. Singleton, K.G. Cassman, and K. Keane. 1996. Residual phosphorus and long-term management strategies for an Ultisol. Plant and Soil, 184: 47-55.

McArthur, W.M. 1991. Reference Soils of South-western Australia. Department of Agriculture, Western Australia, Perth.

McCallister, D.L., M.A. Bahadir, and J.M. Blumenthal. 2002. Phosphorus partitioning and phosphatase activity in semi-arid region soils under increasing crop growth intensity. Soil Sci., 167: 616-624.

McCracken, K.L., W.H. McDowell, R.D. Harter, and C.V. Evans. 2002. Dissolved organic carbon retention in soils: comparison of solution and soil measurements. Soil Sci. Soc. Am. J., 66: 563-568.

McKeague, J.A. and P.A. Schuppli. 1985. An assessment of EDTA as an extractant of organic-complexed and amorphous forms of Fe and Al in soils. Geoderma, 35: 109-118.

Monreal, C.M., H. R. Schulten, and H. Kodama. 1997. Age, turnover and molecular diversity of soil organic matter in aggregates of a Gleysol. Can. J. Soil Sci, 77: 379-388.

Murphy, J. and J.P. Riley. 1962. A modified single-solution method for the determination of phosphate in natural water. Analytica Chimica Acta, 27: 31-36.

Nelson, N.S. 1987. An acid-persulfate digestion procedure for determination of phosphorus in sediments. Comm. Soil Sci. Plant Anal., 18: 359-369.

Noble, A.D., I. Zenneck, and P.J. Randall. 1996. Leaf litter ash alkalinityand neutralisation of soil acidity. Plant and Soil, 179: 293-302.

Oades, J.M. 1995. An overview of processes affecting the cycling of organic carbon in soils. In: R. G. Zepp and C. Sonntag (Eds.), Role of Non-living Organic Matter in Earth's Carbon Cycle. John Wiley and Sons, pp 293-303.

Olsen, S.R. and L.E. Sommers. 1982. Phosphorus. In: A. L. Page, *et al.*, (Eds), Methods of Soil Analysis. Part 2, Chemical and Microbiological Properties. ASA-SSSA, Madison, pp 402-430.

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate Circular 939. US Department of Agriculture, Washington DC.

Payne, R.W., P.W. Lane, A.E. Ainsley, K.E. Bicknell, P.G.N. Digby, S.A. Harding, P.K. Leech, H.R. Simpson, A.D. Todd, P.J. Verrier, and R.P. White. 1987. Genstat 5 Reference Manual. Clarendon Press, Oxford.

Powlson, D.S. and D.S. Jenkinson. 1976. The effects of biocidal treatments on metabolism in soil. II. Gamma radiation, autoclaving, air-drying and fumigation. Soil Biology and Biochemistry, 8: 179-188.

Rayment, G.E. and F.R. Higginson. 1992. Australian Laboratory Handbook of Soil and Water Chemical Methods. Inkata Press, Melbourne.

Ruhlmann, J. 1999. A new approach to estimating the pool of stable organic matter in soil using data from long-term field experiments. Plant and Soil, 213: 149-160.

Serrasolsas, I. and P.K. Khanna. 1995. Changes in heated and autoclaved forest soils of S.E. Australia. II. Phosphorus and phosphatase activity. Biogeochem, 29: 25-41.

Sollins, P., P. Homann, and B.A. Caldwell. 1996. Stabilization and destabilization of soil organic matter: mechanisms and controls. Geoderma, 74: 65-105.

Speir, T.W., J.C. Cowling, G.P. Sparling, A.W. West, and D.M. Corderoy. 1986. Effects of microwave radiation on the microbial biomass, phosphatase activity and levels of extractable N and P in a low fertility soil under pasture. Soil Biol. Biochem, 18: 377-382.

Strong, D.T., P.W.G. Sale, and K.R. Helyar. 1999. The influence of the soil matrix on nitrogen mineralisation and nitrification. IV. Texture. Aust. J. Soil Res., 37: 329-344.

Suhadi. 2002. Development of balanced fertilization in Indonesia, Online at: http://www.fertilizer.org/ifa/publicat/PDF/2002_singapore_suhadi_slides.pdf (verified 21 July).

Tabatabai, M.A. 1994. Soil enzymes. In: R. W. Weaver, S. Angle, P. Bottomley, D. Bezdicek, S. Smith, M.A. Tabatabai, A. Wollum (Eds.), Methods of Soil Analysis. Part 2. Microbiological and Biochemical Properties., SSSA Inc., Madison, WI.

Tang, C., C.P. Sparling, C.D.A. McLay, and C. Raphael. 1999. Effect of short-term residue decomposition on soil acidity. Aust. J. Soil Res., 37: 561-573.

Theng, B.K.G., K.R. Tate, and P. Becker-Heidmann. 1992. Towards establishing the age, location, and identity of the inert soil organic matter of a Spodosol. Zeitschrift fur Pflanzenernahrung und Bodenkunde, 155: 181-184.

Turrion, M.B., J.F. Gallardo, L. Haumaier, M.I. Gonzalez, and W. Zech. 2001. 31P-NMR characterization of phosphorus fractions in natural and fertilized forest soils. Annals of Forest Science, 58: 89-98.

Wagai, R. and P. Sollins. 2002. Biodegradation and regeneration of water-soluble carbon in forest soil: leaching column study. Biol. Fert. Soils, 35: 18-26.

Williams, J.D.H., J.K. Syers, T.W. Walker, and R.W. Rex. 1970. A comparison of methods for determination of soil organic phosphorus. Soil Sci., 110: 13-18.

Wu, J., Z.L. He, W.X. Wei, A.G. O'Donnell, and J.K. Syers. 2000. Quantifying microbial biomass phosphorus in acid soils. Biol. Fert. Soils, 32: 500-507.

Yang, Y., D. Ratte, B.F. Smets, J.J. Pignatello, and D. Grasso. 2001. Mobilization of soil organic matter by complexing agents and implications for polycyclic aromatic hydrocarbon desorption. Chemosphere, 43: 1013-1021.

Zoysa, A.K.N., P. Loganathan, and M.J. Hedley. 1999. Phosphorus utilisation efficiency and depletion of phosphate fractions in the rhizosphere of three tea (*Camellia sinensis* L.) clones. Nutrient Cycling in Agroecosystems, 53: 189-201.