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Soil Organic Carbon Losses: The Balance between Respiration and Leaching, and Phosphorus Mobility in Lateritic Soils

Fadly Hairannoor Yusran[1]

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ABSTRACT

Soil Organic Carbon Losses: The Balance between Respiration and Leaching, and Phosphorus Mobility in Lateritic Soils (FH Noor): Organic matter (OM) application may contribute to managing lateritic soils by improving aspects of physical, chemical, and biological fertility. However, the finite persistence of organic carbon (OC), the main component of soil organic matter (SOM), may limit the usefulness of OM addition because decomposition and C leaching promotes C loss from the soil, especially in tropical regions. The main objectives of this study were to determine the balance and dynamics of soil OC (SOC) due to mineralisation and leaching processes and the relationship of these processes to P mobility in soil. Two lateritic soils of Western Australia were used. Both soils were packed into plastic columns and water was added to simulate two rainfall regimes: tropical (4,000 mm year ^{1}) and subtropical (900 mm year ^{1}). Three types of OM (peat, wheat straw, and lucerne hay) were added at the equivalent of 80Mg ha ^{1}. Soils were watered weekly to supply one year's rainfall over a period of six months. Carbon loss from leaching contributed 1.4% of the total C, whilst respiration accounted for 10.4%. The Ultisol with a sandy texture had more C loss in leachate than the Oxisol with higher clay content, for the simulated tropical rainfall. The subtropical rainfall regime resulted in more respiration than the tropical rainfall regime. Downward movement of dissolved organic carbon (DOC) changed the distribution of non-extractable phosphorus (NP) and bicarbonate phosphorus (BP) in the leaching column, as well as the dislocation of extractable Al and Fe.

Keywords: Carbon loss, organic matter persistence, Oxisol, phosphorus mobility, podzolisation, Ultisol

INTRODUCTION

Soils play an effective role as a sink or storage for C, and as a source or loss of C to pools outside the soil system. The balance between storage and loss depends on soil management, as well as climate and soil properties. The losses of C from soil are mainly from SOM decomposition (respiration), erosion, and leaching (Akala and Lal 2000). In forest soils, C leaching contributes between 6-46% of total-C loss as DOC (Cronan 1985; Magill and Aber 2000). Investigations of C balance have focused on the effect of temperature on C mineralisation (Liechty *et al.* 1995; Tate *et al.* 1993; Zogg *et al.* 1997), which is only effective in surface soil (MacDonald *et al.* 1999). The leaching of DOC from soil may return to the atmosphere as CO_2 loss from streams, lakes, or oceans (Kling *et al.* 1991). For soils in the tropics, the balance between upward (respiration) and downward (DOC leaching) loss could be important, especially for lateritic soils if the effectiveness of SOM application is to be understood. Heavy rainfall may be an additional factor in increasing OC loss from soil, not only in erosion but also in infiltration of water through the soil profile.

Phosphorus adsorption, measured by phosphate buffering capacity and phosphate retention index, was correlated with soil organic phosphorus (SOP) in soils from Western Australia (Brennan *et al.* 1994). Phosphate buffering capacity was also correlated with SOC, Al, and Fe contents in Inceptisols in India (Patiram and Prasad 1990). In other studies, SOC was positively correlated with the activity of phosphatase, especially in acid soils (Baligar *et al.* 1999; Barrett *et al.* 1998; Canarutto *et al.* 1995). The increases of SOP content generally associated with

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[1] Soil Department, Faculty of Agriculture, Lambung Mangkurat University, Banjarbaru 70714, South Kalimantan. E-mail: fhyusran@yahoo.com.au

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increases in SOC (Iyamuremye and Dick 1996; Reddy *et al.* 2000). Thus, if leaching of OC is prominent in these soils, and OP affects P adsorption (Brennan *et al.* 1994), this leaching will also have an effect on P mobility in the soil profile. Working with soil columns, Chardon *et al.* (1997) found that 90% of total-P (TP) in leachate was in the form of dissolved organic phosphorus (DOP) and that leaching was related to DOC. Rupp *et al.* (2002) suspected that the decreasing redox potential might be responsible for the increasing P solubility as well as DOC, and intensifying the leaching of both.

The decomposition of SOM is associated with the release of P from adsorption sites (Dalal, 1979; Gressel *et al.* 1996; Maroko *et al.* 1999). In this process, mechanism such as organic ligand exchange (Hinsinger 2001; Iyamuremye and Dick 1996) is responsible as part of dissolution and desorption of phosphate (Burkitt *et al.* 2002; MacKay *et al.* 1986; McBride, 1994; Rhue and Harris, 1999). For temperate forest soils, changes in SOP are closely related to changes in SOM composition (Gressel *et al.* 1996), although this study was limited to topsoil. Information on the relationship between SOC and SOP in the profile of lateritic soils is limited, especially in the tropics. Such information may be of special importance in the tropics where SOM decomposition is very rapid and may affect P dynamics. Additionally, P dynamics would be related to the activity of soil micro-organisms as indicated by the increase in phosphatase activity (Joner and Jakobsen 1995) and microbial biomass phosphorus (MBP) (Oberson *et al.* 1995) where OM is applied to the soil.

As the adsorption and the release of P is related to SOC (Brennan *et al.* 1994), whilst Al and Fe-hydroxides are factors in phosphate adsorption (Haynes and Mokolobate 2001), the mobility of SOC may affect the sesquioxides concentrations through soil profile. In high rainfall tropical areas, these mechanisms may occur to the deeper profile of lateritic soils due to higher leaching.

In summary, OP has an impact on P cycles in soils. To a greater extent, DOP is the predominantly present in subsoil of leaching columns (Chardon *et al.* 1997). The turnover of DOP, together with DOC and DON, is a major pathway in nutrient cycling and may have more impact than previously assumed (Kalbitz *et al.* 2000). In lateritic soils, these impacts could be more complicated due to the role of Al and Fe-oxides in soils which may also change with leaching of OC. These issues need to be explained in order to understand mechanisms involved in P mobility in lateritic soils.

The objectives of this experiment were to compare fluxes of SOC and SOP in two different lateritic soils, by: (1) studying the effect of rainfall regimes relevant to tropical and subtropical environments on the loss of C from soil profile, and (2) measuring the effect of leaching on the change of SOC, soil extractable-P, and extractable-Al and Fe with depth in the soil.

MATERIALS AND METHODS

Experimental Setup

This leaching column (PVC plastic, 90x5.7 cm) experiment was set in factorial using a completely randomised block design. The treatments were: 1) Two soils (Ultisol, Typic kandiudult; and Oxisol, Plinthic eutrudox), 2) Two rainfall simulations: tropical (4,000 mm year ^{1} equivalent) and subtropical (900 mm year ^{1} equivalent). These are about the same as in South Kalimantan, Indonesia, and Perth metro area, Western Australia, and 3) Four OM sources: control, peat, wheat straw, and lucerne hay. The OM rate was 80 Mg ha ^{1}.

Data were analysed statistically with GenStat (Payne *et al.* 1987). Analysis of variance was followed by mean comparison (orthogonal polynomial contrasts) if the treatment was significant. Correlation was carried out using SPSS (Coakes 2001) to determine any relationships between parameters.

Procedures

An Ultisol from Western Australia was collected near Jarrah (*Eucalyptus marginata*) forest, near Jarrahdale, and an Oxisol from near Bunbury. Both soils were selected due to high content of extractable-Al and Fe (McArthur 1991), in order to see their effects on phosphate adsorption and P mobility throughout the leaching columns. Some soil characteristics were presented previously (Yusran 2008) (Table 1). Samples were taken from the lower horizon in the profile (20-25 cm) where the amount of SOM was less but the amount of extractable-Al and Fe were expected to be higher.

In order to simulate a combination of leaching processes and wet-dry conditions, water equivalent to one year's rainfall was added to each column; the equivalent annual rainfall was distributed in equal increments applied weekly. Gradual watering was applied using a dripper made from plastic bottle. With the bottom open, the bottles were positioned upside down on the top of leaching columns. A 0.2 mm millipore filter (25 mm, supor membrane, non sterile,

Table 1. Some characteristics of soils (Ultisol and Oxisol) used in leaching columns.

Soil characteristic	Subsurface regolith	Ultisol (Typic kandiudult)	Oxisol (Plinthic eutrodox)
[1]Texture			
Sand (%)	48	89	60
Silt (%)	45	5	9
Clay (%)	7	6	31
[2]DOC (mg kg^{-1})	3 ± 0.80	30 ± 3.00	13 ± 3.10
[3]Org-C (g kg^{-1})	0.35	5.80	2.80
[3]Total-N (g kg^{-1})	0.29	0.20	0.15
[4]Total-P (mg kg^{-1})	235 ± 5.50	57 ± 3.20	83 ± 6.70
[5]Bicarb. P (mg kg^{-1})	26 ± 2.10	7.0 ± 0.90	8.0 ±1.20
pH (1:5 soil:H_2O)	6.8 ± 0.06	6.2 ± 0.12	6.2 ± 0.20
[6]Oxalate-Al (g kg^{-1})	1.0 ± 0.19	11.1 ± 1.00	11 ± 2.00
[6]Oxalate-Fe (g kg^{-1})	18.0 ± 1.00	73.0 ± 3.00	274 ± 7.00

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

Pall Gelman Laboratory) was fixed at the lid of every bottle to ensure a realistic rate of water delivery. After 24 hours of water application, a suction mechanism (10 cm water) was applied to all leachate containers for another 24 hours to avoid water saturation and reducing conditions at the bottom of every column.

Soil in each column was divided into seven layers. The first layer (0-10 cm) was the mixture of treatment and soil sample (Figure 1).

Soil packing was performed with soil bulk density as an indicator, where Ultisol was 1.32 g cm^3 and for Oxisol was 1.13 g cm^3. The internal diameter of a leaching column was 5.7 cm; total volume of water for the tropics was 7,655 mL and for the subtropics was 2,297 mL. Before the first application of water, soils were wet to 60% water holding capacity. The edge-flow effect due to plastic column was reduced by using funnel o-rings (0.6 cm thick) made from Styrofoam on every layer of soil. The o-ring fitted tightly inside the column. Soil mesh was applied on every layer on the top of o-ring. To evenly distribute water dripping, a filter paper was placed on the top of the OM layer. The filter paper needed to be changed every two weeks to avoid decomposition.

Soil sampling

To follow the mobility of DOC and other factors affecting it at the end of the experiment, sampling was done on six layers of the leaching columns (10-20, 20-30, 30-40, 40-50, 50-60, and 60-70 cm). With

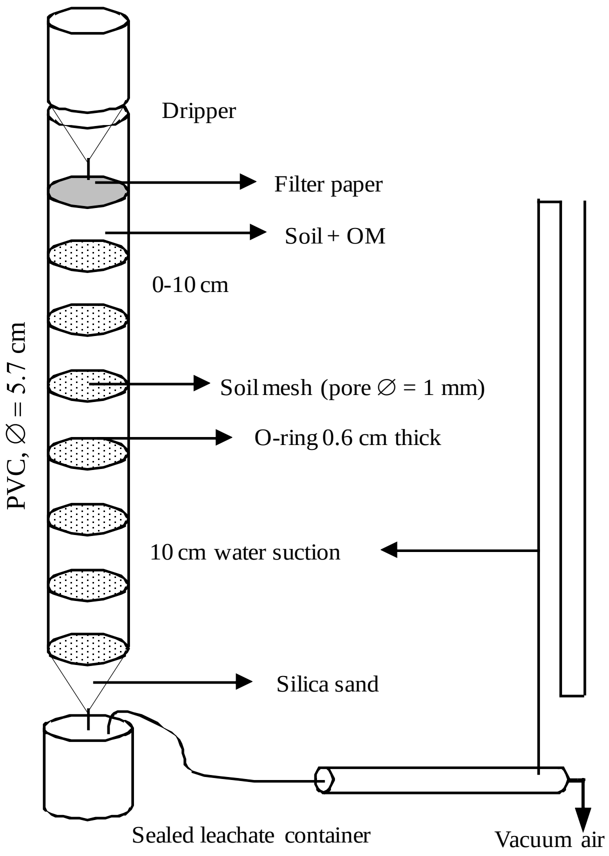

Figure 1. Leaching column with six layers of soil and one layer of soil + organic matter. Suction apparatus (right part of the graph) was set at 10 cm water.

48 leaching columns, there were 288 soil samples. Leachate was collected for further analysis.

Measurements

Bicarbonate-P was extracted using 0.5 *M* $NaHCO_3$ at pH 8.5. This is a modification from a method by Olsen *et al.* (1954) described by Rayment and Higginson (1992). The manual colorimetric method for determination of phosphate in the extract was based on that of Murphy and Riley (1962). Non-extractable-P was conducted by measuring TP with acid-persulphate digestion (Nelson 1987) and then subtracting the results of the BP content of the same soil calculated beforehand. Dissolved reactive-P (DRP) was measured directly in leachate after filtration with 0.2 μm millipore filter (25 mm, supor membrane, non sterile, Pall Gelman Laboratory) using the method of Rayment and Higginson (1992). Soil respiration was according to Anderson (1982). Modification was made in time period that alkaline trap (0.5 *M* KOH) was exposed to soil inside the headspace of the leaching column.

Total-P was measured in layers of leaching column using procedures for TP in soils based on the persulphate digestion procedure by Nelson (1987). Total-P in the leachate was based on procedures outlined by Rayment and Higginson (1992). The principle of this method is to convert OP and other P fractions (*e.g.* particulate) in leachate by digestion (HNO_3 and H_2SO_4) into soluble phosphate. Phosphate content was measured using the spectrophotometric method of Murphy and Riley (1962). Dissolved-organic-C measurement was from the method by Wagai and Sollins (2002). Dissolved-organic-C in leachate was determined using filtered leachate (0.2 mm millipore filter; 25 mm, supor membrane, non sterile, Pall Gelman Laboratory). A Shimadzu TOC-5000A instrument was used to measure OC as NPOC (Non-purgeable Organic Carbon). Extractable Al and Fe were according to Rayment and Higginson (1992) using an extractant of 0.2 M acid ammonium oxalate pH 3.0 with soil:extractant ratio of 1:100. Leachate pH was measured directly in the leachate using a combined pH-reference electrode.

RESULTS AND DISCUSSION

The high leaching of DOC in the Ultisol treated with tropical rainfall following application of wheat straw may have been related to the higher C content of wheat straw residue (Table 2). Recalcitrant soluble organic compounds from peat are likely to remain in soil for longer period of time, in contrast to the easily-decomposable, simple organic acids from lucerne hay or wheat straw. However, C loss from leaching was not as much as C loss from respiration. Even though the respiration decreased over time (Figure 2), the overall C loss was much higher than that of leaching process (Table 3 and Table 4).

Subtropical rainfall showed a higher respiration rate in both soils compared to tropical rainfall. The magnitude of C loss from respiration with tropical rainfall ranged between 1 to 10 times higher in control and in soil with wheat straw treatment than that of leaching. In columns receiving subtropical rainfall, C loss from respiration ranged between 7 to 36 times higher in control and in soil with wheat straw treatment (Table 4). Columns receiving tropical rainfall also had higher C loss due to leaching, but columns receiving subtropical rainfall had more C loss due to respiration. Not only did DOC leach from the columns, but soluble OM concentrations increased in the deeper layers of soil in columns Figure 3. This effect was also observed by Rumpel *et al.* (2002) and Brye *et al.* (2001), and may represent a mechanism for podzolisation (Egli *et al.* 2003; Ugolini *et al.* 1987).

Podzolisation involves the loss of some cations from surface soil horizons (Egli *et al.* 2003), and this experiment also showed this effect on extractable-Al and Fe content in the leachate, especially in the Oxisol. In the leaching columns, there was an interaction ($p \leq 0.01$) between type of soil and column layers on extractable-Al and Fe contents indication the mobility of those cations (Figure 5). Consequently, longer exposure to high rate of rainfall (more than the time of the experiment) may also have leached extractable-Al and Fe through the Ultisol columns.

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

Source of carbon	[1]Total-N ($g\ kg^{-1}$)	[1]Total-C ($g\ kg^{-1}$)	C/N ratio	[2]Total-P ($g\ kg^{-1}$)
Peat	0.56	31.5	56	0.16
Wheat straw	0.76	43.4	57	0.20
Lucerne hay	2.69	41.4	15	0.25

[1]Leco C and N analyser, [2] wet combustion for wheat straw and lucerne, dry combustion for peat; both measured with Rayment and Higginson (1992).

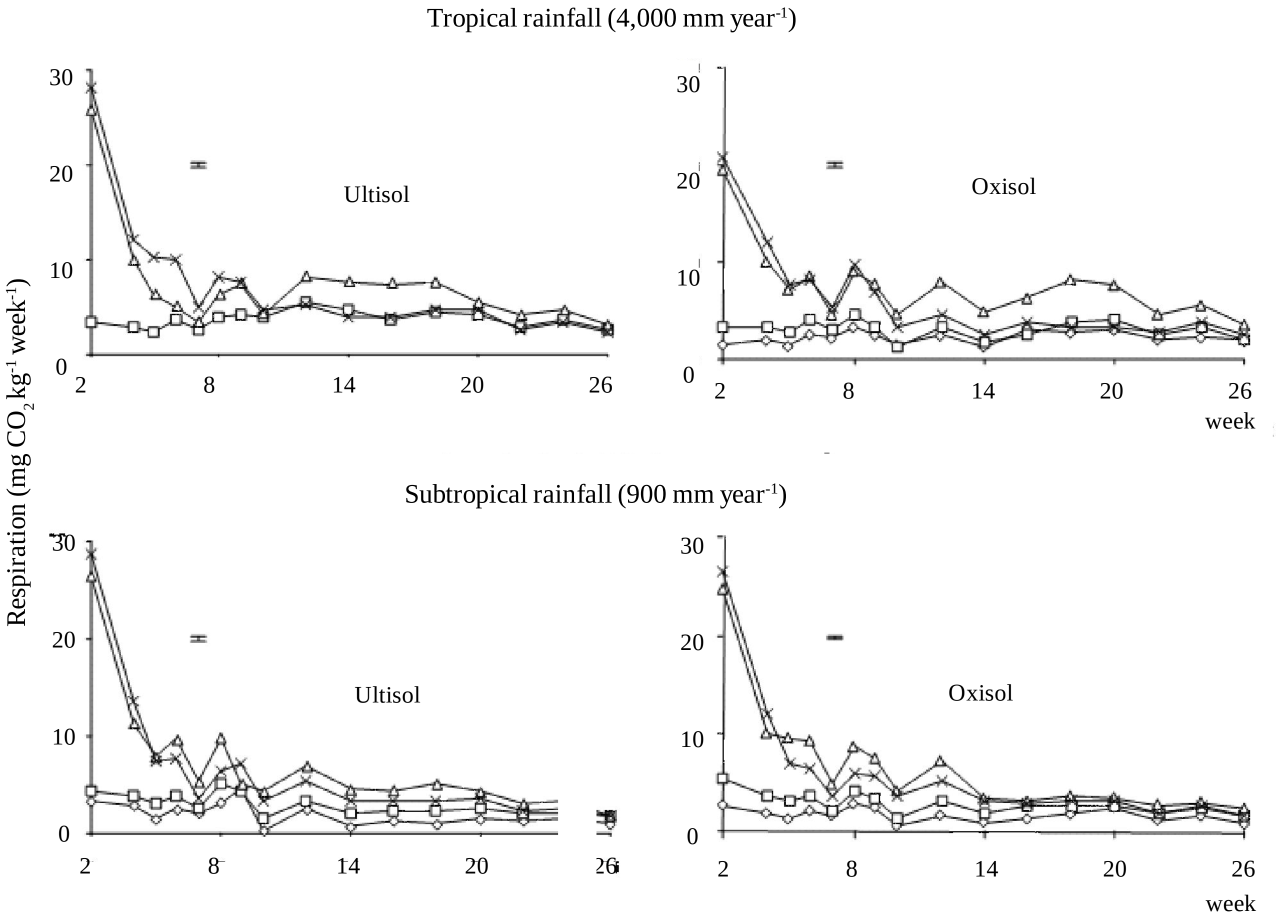

Figure 2. Soil respirations throughout the experiment (26 weeks) due to organic matter applications (80 Mg ha^{-1}) in two different soils. ◇ = control, □ = peat, △= wheat straw, and × = lucerne hay. Bar in each graph represent LSD 5% for organic matter.

In spite of a significant effect on DOC concentration in leachate due to OM treatment, rainfall, and type of soil, there was non-significant DRP content in leachate. However, the non-significant trend was similar to the significant trend in of DOC (Figure 3), where wheat straw showed the greatest effect followed by lucerne hay and peat. This trend in DRP could be the explanation why this P pool contributes to the problem of water body, *i.e.* eutrophication (Liikanen *et al.* 2004; McDowell and Sharpley 2004).

There was an increase of concentration at the top layer of the column. This occurred in columns treated with wheat straw with tropical rainfall. A similar trend was also observed for TP. Observations by Kleinman *et al.* (2003) who also observed that there was an increase of P (oxalate and Mehlich 3-extractable) in the deeper layers of leaching columns, and there was poor correlation of soil P fractions with leachate P. Kleinmann *et al.* (2003) suggested that translocation of P due to preferential flow of P via macropores (bypass leaching) might have taken place.

A closer inspection of the distribution pattern of BP along the leaching column reveals that there was an initial deposition of BP at the first 10 cm from the soil surface. Working with soil samples from 0-5 cm depth, Koopmans *et al.* (2003) found an accumulation of IP (extracted with EDTA) after manure applications. This could be similar to the process of BP deposition in this experiment, but with intermittent occurrence with deposition. According to Kleinman *et al.* (2003), P leaching losses often occur in discrete events or pulses that can be easily missed and to monitor this effect continuously requires expensive equipment. The fluctuation of P might have been due to the process of mobilisation and resorption at the wall of macropores (Jensen *et al.* 1999). Working with glucose as a source of C in soil column, Jensen *et al.* (1999) predicted the role of high C content

Table 3. Cumulative carbon loss (%) from leaching following application of different organic matter at 80 Mg ha^{-1} after 24 weeks in two soils and two rainfall simulations.

Organic matter source	Rainfall			
	Tropical		Subtropical	
	Ultisol	Oxisol	Ultisol	Oxisol
Control	0.13^{c}	0.15^{c}	0.04^{a}	0.05^{a}
Peat	0.10^{b}	0.10^{b}	0.03^{a}	0.04^{a}
Wheat straw	0.22^{d}	0.14^{c}	0.04^{a}	0.05^{a}
Lucerne hay	0.16^{c}	0.10^{b}	0.04^{a}	0.04^{a}

Numbers followed by the same letters in superscript indicate differences according to LSD 5% (0.032).

Table 4. Cumulative carbon loss (%) from soil respiration following application of different organic matter at 80 Mg ha^{-1} after 24 weeks in two soils and two rainfall simulations.

Organic matter source	Rainfall			
	Tropical		Subtropical	
	Ultisol	Oxisol	Ultisol	Oxisol
Control	0.18^{a}	0.29^{b}	0.19^{a}	0.30^{b}
Peat	0.30^{b}	0.45^{c}	0.24^{ab}	0.46^{cd}
Wheat straw	0.57^{e}	1.05^{h}	0.59^{e}	1.00^{gh}
Lucerne hay	0.54^{de}	0.94^{fg}	0.46^{cd}	0.88^{f}

Numbers followed by the same letters in superscript indicate differences according to LSD 5% (0.084).

(1,000 mg glucose-C L^{-1}), Al and Fe(III)(hydr)oxide, and redox condition in creating the fluctuation. This mechanism might taken place in our experiment.

An interesting result was observed for NP throughout the soil in leaching column. Non-extractable-P was correlated with DOC in Ultisol leaching column (Table 6) and the distribution of NP was similar to that of DOC (Figure 6). Both showed linear trends with depth ($p \leq 0.05$, orthogonal polynomial contrast). More NP and DOC were recorded at greater depth in the columns indicating leaching and deposition processes. In the Oxisol, the deposition of NP took place at 20-30 cm depth in the column. The high content of Fe in the Oxisol (Table 1) might derive amourphous Fe sesquioxides which can adsorb this pool of P by ligand exchange with surface hydroxyls, especially OP from inositol (Turrion *et al.* 2001). Considering the effect of mobilisation and resorption on BP and TP in this experiment, NP on the other hand, was not affected by such mechanisms and transported more freely to the deeper layers of the column. As for NP in leaching columns, there were significant linear trends ($p \leq 0.01$) in Al and Fe distribution throughout the leaching column.

In the Oxisol - probably due to higher content of extractable-Al and Fe (Table 1) - both Al and Fe were more mobile. Soil pH might also responsible for their mobility. Even though soil pH was not affected, SOM decomposition created more acid leachate, especially at a subtropical rainfall rate. This acid leachate was probably more easily to transport extractable-Al and Fe throughout the leaching columns. As a result, extractable-Al and Fe deposited at the deeper layers or even leached away. This mechanism confirms the hypothesis that organic matter addition will affect not only soil organic-C content of the soil, but also non-extractable-P, extractable-Al, extractable-Fe, and pH (Yusran 2008).

Figure 7 summarises average C mobility and loss in Ultisol column treated with tropical rainfall and 80 Mg ha^{-1} wheat straw. Respiration was the highest C flux, followed by leaching and deposition. The

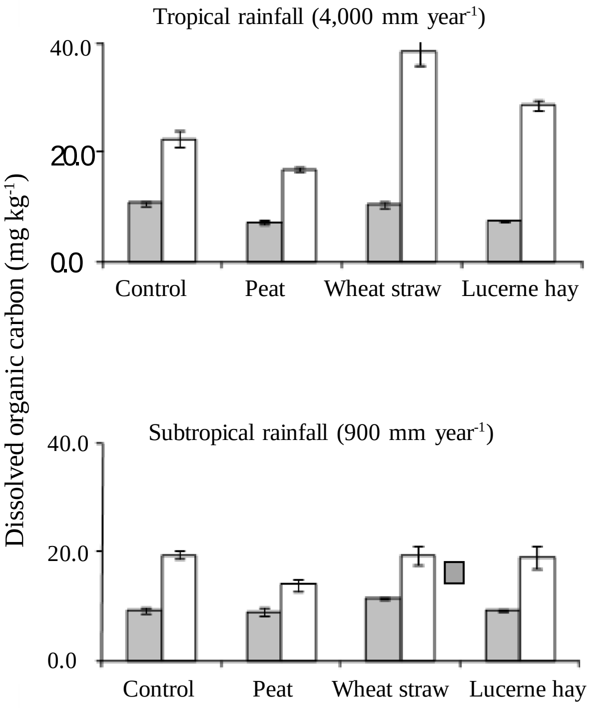

Figure 3. Cumulative dissolved organic carbon in leachate expressed per mass of soil after treatment with organic matter in two soils (■ = Ultisol and ☐ = Oxisol) and in two rainfall simulations. Line in each bar indicates the standard error.

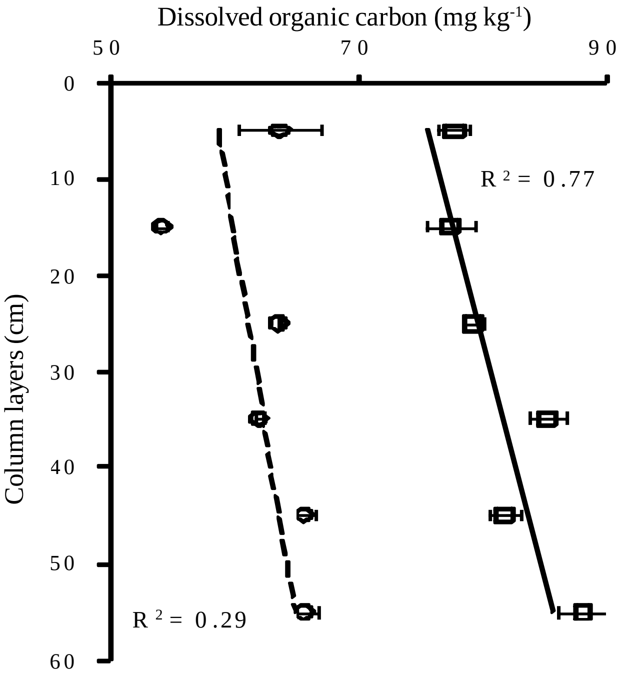

Figure 4. Dissolved organic carbon concentration throughout the leaching column treated with wheat straw and tropical rainfall. R^2 = coefficient of determination from linear trend line and data plot. —-O— = Ultisol, and —☐— = Oxisol. Bar in every observed point is the standard error.

Table 5. Balance between respiration and leaching on every treatment, calculated from loss (%) due to respiration divided by loss (%) due to leaching.

Organic matter source	Rainfall			
	Tropical		Subtropical	
	Ultisol	Oxisol	Ultisol	Oxisol
Control	1.4 ± 0.13	2.0 ± 0.20	4.8 ± 0.48	6.9 ± 1.21
Peat	3.2 ± 0.32	4.8 ± 0.46	9.4 ± 1.30	11.4 ± 1.96
Wheat straw	2.7 ± 0.48	8.1 ± 1.25	16.7 ± 2.96	18.9 ± 0.46
Lucerne hay	3.4 ± 0.26	9.7 ± 0.46	13.7 ± 2.94	21.1 ± 0.86

total C loss from the original pool (soil organic C + wheat straw treatment at 80 Mg ha^{-1}) was about 0.8%.

CONCLUSIONS

Respiration contributed to C loss ranging from 0.2-1.00% of total-C in soils, regardless of the rainfall rate. A small percentage of C loss occurred *via* leaching (0.03-0.05% of total-C for subtropical and 0.10-0.22% of total-C for tropical rainfall regimes). Respiration therefore contributed 1-36 times higher C loss than leaching. However, at a tropical rate of rainfall, the leaching process was as important as respiration as a C loss mechanism, and could reduce the persistence of added organic matter. There was no evidence of BP and NP leaching from the columns, but there was an inconsistent distribution of BP and linear distribution of NP within the leaching columns. Added OM had an impact on the distribution of soil BP, NP and DOC as well as sesquioxides down the

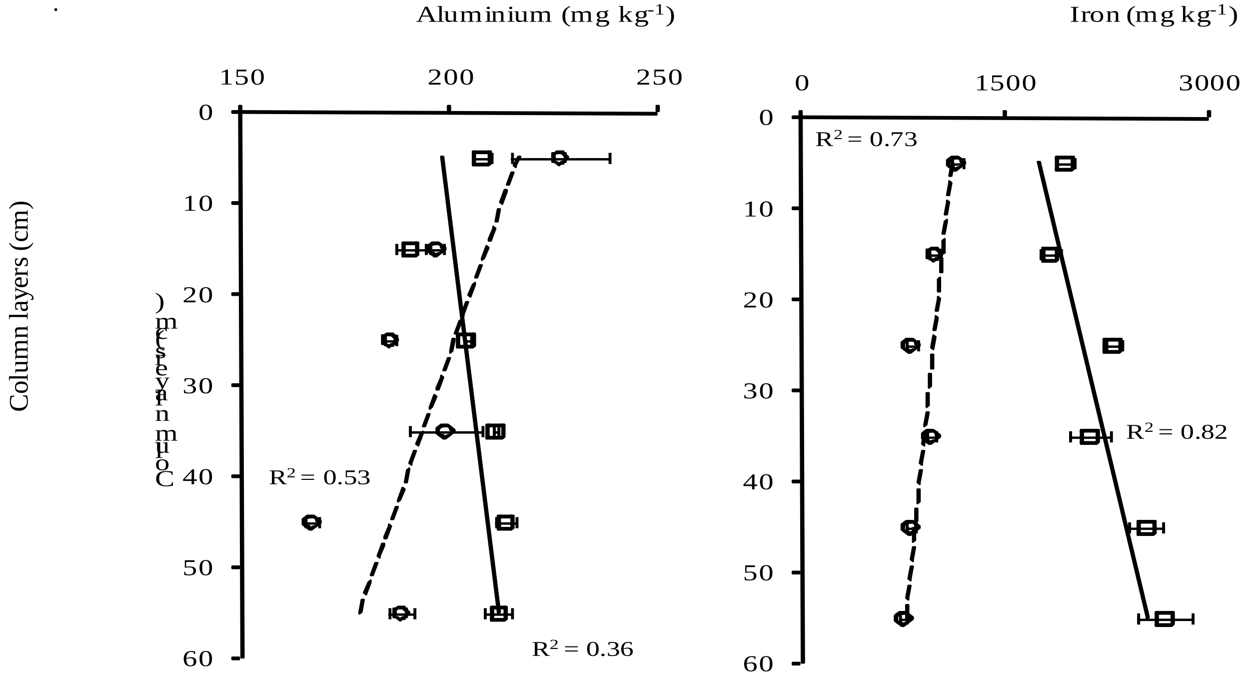

Figure 5. Extractable aluminium and iron distribution in leaching column treated with wheat straw and tropical rainfall. R^2 = coefficient of determination from linear trend line and data plot. —○— = Ultisol, and —□— = Oxisol. Bar in every observed point is the standard error.

Table 6. Correlation all parameters in the leaching column. Only significant correlations are presented. * represents a significant (p dd 0.05) and ** a highly significant ($p \leq 0.01$) correlation.

	TP	*BP*	*NP*	*Al*	*Fe*	*pH*	*DOC*
TP							
BP	0.47^{**}						
NP	0.97^{**}						
Al							
Fe	0.54^{**}		0.59^{**}	0.42^{*}			
pH							
DOC	0.49^{**}		0.56^{**}		0.76^{**}		

TP = Total Phosphorus, BP = Bicarbonate Phosphorus, NP = Non-extractable Phosphorus, and DOC = Dissolved Organic Carbon. n = 48.

leaching columns. Dissolved-OC was the most readily leached from within the six months period. There was an indication that BP and NP will be leached away with longer period of time, especially in sandy soil with higher rainfall. In these scenarios, if OM amendments were to be applied to lateritic soils, climatic factors, *i.e.* rainfall, need to be taken into account in order to make amendments more effective and efficient. Moreover, to test the effectiveness of OM amendments, *in situ* research is likely to be the most advantageous approach to be employed.

REFERENCES

Akala VA and R Lal. 2000. Potential of mine land reclamation for soil organic carbon sequestration in Ohio. *Land Degrad Dev* 11: 289-297.

Anderson JPE. 1982. Soil respiration. In: AL Page, RH Miller and DR Keeney (eds). Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties' 2nd ed.. ASA. Monograph No. 9. ASA-SSSA, Madison, WI, pp. 831-871.

Baligar VC, RJ Wright, NK Fageria and GVE Pitta. 1999. Enzyme activities in cerrado soils of Brazil. *Comm Soil Sci Plant Anal* 30: 1551-1560.

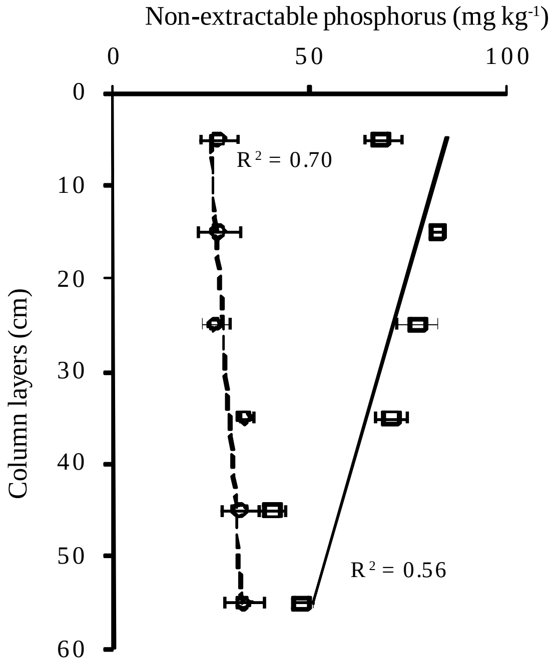

Figure 6. Non-extractable phosphorus distribution in leaching column treated with wheat straw and tropical rainfall. R^2 = coefficient of determination from linear trend line and data plot. —○— = Ultisol, and —□— = Oxisol. Bar in every observed point is the standard error.

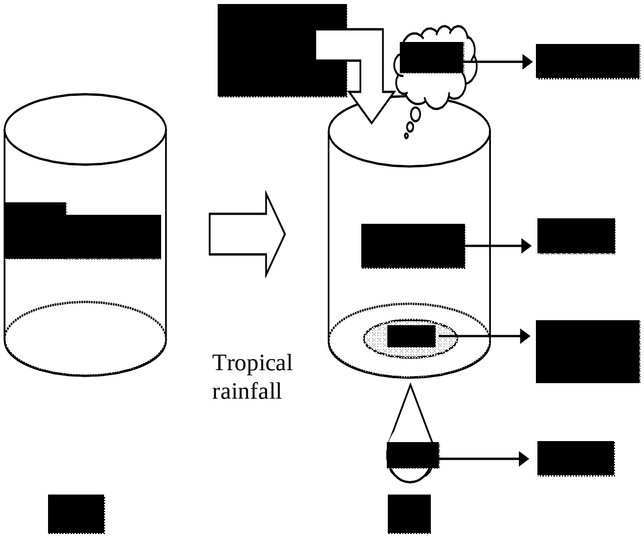

Figure 7. Carbon losses (respiration and leaching) and deposition due to tropical rainfall (4.000 mm $year^{-1}$) in soil (Ultisol) column treated with wheat straw (80 Mg ha^{-1}).

Barrett DJ, AE Richardson and RM Gifford. 1998. Elevated atmospheric CO_2 concentrations increase wheat root phosphatase activity when growth is limited by phosphorus. *Aust J Plant Phys* 25: 87-93.

Brennan RF, MDA Bolland, RC Jeffery and DG Allen. 1994. Phosphorus adsorption by a range of Western Australian soils related to soil properties. *Comm in Soil Sci Plant Anal* 25: 2768-2795.

Brye KR, JM Norman, LG Bundy and ST Gower. 2001. Nitrogen and carbon leaching in agroecosystems and their role in denitrification potential. *J Envir Qual* 30: 58-70.

Burkitt LL, PW Moody, CJP Gourley and MC Hannah. 2002. A simple phosphorus buffering index for Australian soils. *Aust J Soil Res* 40: 497-513.

Canarutto S, M Mazzoncini, A Perna and S Cervelli. 1995. The effect of reduction of inputs on phosphatase activity, organic carbon content and water stability index in a corn cultivated soil. *Fresenius Envir Bull* 4: 291-296.

Chardon WJ, O Oenema, P del Castilho, R Vrisema, J Japenga and D Blaauw. 1997. Organic phosphorus in solutions and leachates from soils treated with animal slurries. *J Envir Qual* 26: 372-378.

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

Cronan CS 1985. Comparative effects of precipitation acidity on three forest soils: carbon cycling responses. *Plant Soil* 88: 101-112.

Dalal RC. 1979. Mineralization of carbon and phosphorus from carbon-14 and phosphorus-32 labelled plant material added to soil. *Soil Sci Soc Am J* 43: 913-916.

Egli M, A Mirabella, G Sartori and P Fitze. 2003. Weathering rates as a function of climate: results from a climosequence of the Val Genova (Trentino, Italian Alps). *Geoderma* 111: 99-121.

Gressel N, JG McColl, CM Preston, RH Newman and RF Powers. 1996. Linkages between phosphorus transformations and carbon decomposition in a forest soil. *Biogeochemistry* 33: 97-123.

Haynes RJ and MS 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. *Nutr Cycl Agroecos* 59: 47-63.

Hinsinger P. 2001. Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. *Plant Soil* 237: 173-195.

Iyamuremye F and RP Dick. 1996. Organic amendments and phosphorus sorption by soils. *Adv Agron* 56: 139-185.

Jensen MB, HCB Hansen, NE Nielsen and J Magid. 1999. Phosphate leaching from intact soil column in response to reducing conditions. *Water, Air, Soil Poll* 113: 411-423.

Joner EJ and I Jakobsen.1995. Growth and extracellular phosphatase activity of arbuscular mycorrhizal hyphae as influenced by soil organic matter. *Soil Biol Biochem* 27: 1153-1159.

Kalbitz K, S Solinger, JH Park, B Michalzik and E Matzner. 2000. Controls on the dynamics of dissolved organic matter in soils: a review. *Soil Sci* 165: 277-304.

Kleinman PJA, BA Needelman, AN Sharpley and RW McDowell. 2003. Using soil phosphorus profile data to assess phosphorus leaching potential in manured soils. *Soil Sci Soc Am J* 67: 215-224.

Kling GW, GW Kipphut and MC Miller. 1991. Arctic lakes and streams as gas conduits to the atmosphere: implications for tundra carbon budgets. *Science* 251: 298-301.

Koopmans GF, WJ Chardon, J Dolfing, O Oenema, P van der Meer and WH van Riemsdijk. 2003. Wet chemical and phosphorus-31 nuclear magnetic resonance analysis of phosphorus speciation in a sandy soil receiving long-term fertilizer or animal manure applications. *J. Environ Qual* 32: 287-295.

Liechty HO, E Kuuseoks and GD Mroz. 1995. Dissolved organic carbon in northern hardwood stands with differing acidic inputs and temperature regimes. *J Environ Qual* 24: 927-933.

Liikanen A, M Puustinen, J Koskiaho, T Vaisanen, P Martikainen and H Hartikainen. 2004. Phosphorus removal in a wetland constructed on former arable land. *J Environ Qual* 33: 1124-1132.

MacDonald NW, DL Randlett and DR Zak. 1999. Soil warming and carbon loss from a Lake States Spodosol. *Soil Sci Soc Am J* 63: 211-218.

MacKay AD, JK Syers, RW Tillman and PEH Gregg. 1986. A simple model to describe the dissolution of phosphate rocks in soils. *Soil Sci Soc Am J* 50: 291-296.

Magill AH and JD Aber. 2000. Dissolved organic carbon and nitrogen relationships in forest litter as affected by nitrogen deposition. *Soil Biol Biochem* 32: 603-613.

Maroko JB, RJ Buresh and PC Smithson. 1999. Soil phosphorus fractions in unfertilized fallow-maize systems on two tropical soils. *Soil Sci Soc Am J* 63: 320-326.

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

McBride MB. 1994. Environmental Chemistry of Soils. Oxford University Press, New York.

McDowell RW and AN Sharpley. 2004. Variation of phosphorus leached from Pennsylvanian soils amended with manures, composts or inorganic fertilizer. *Agric Ecos Environ* 102: 17-27.

Murphy J and JP Riley. 1962. A modified single-solution method for the determination of phosphate in natural water. *Anal Chim Acta* 27: 31-36.

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

Oberson A, JM Besson, N Maire and H Sticher. 1996. Microbiological processes in soil organic phosphorus transformations in conventional and biological cropping systems. *Biol Fertil Soils* 21: 138-148.

Olsen SR, CV Cole, FS Watanabe and LA Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. US Department of Agriculture, Circular 939.

Patiram RNR and RN Prasad. 1990. Phosphate adsorption by acid soils from different altitudes. *J Indian Soc Soil Sci* 38: 602-608.

Payne RW, PW Lane, AE Ainsley, KE Bicknell, PGN Digby, SA Harding, PK Leech, HR Simpson, AD Todd, PJ Verrier and RP White. 1987. Genstat 5 Reference Manual. Oxford University Press, Oxford.

Rayment GE and FR Higginson. 1992. Australian Laboratory Handbook of Soil and Water Chemical Methods. Inkata Press, Melbourne.

Reddy DD, AS Rao and TR Rupa. 2000. Effects of continuous use of cattle manure and fertilizer phosphorus on crop yields and soil organic phosphorus in a Vertisol. *Biores Tech* 75: 113-118.

Rhue RD and WG Harris. 1999. Phosphorus sorption/desorption reactions in soils and sediments. In: KR Reddy, GA O'Connor and CL Schelske (eds). Phosphorus Biogeochemistry in Subtropical Ecosystems. Lewis Publishers, Boca Raton, Florida, pp. 187-206.

Rumpel C, I Kogel-Knabner and F Bruhn. 2002. Vertical distribution, age, and chemical composition of organic carbon in two forest soils of different pedogenesis. *Org Geochem* 33: 1131-1142.

Rupp H, K Kalbitz and R Meissner. 2002. Impact of land use changes in the Dromling fen area on nutrient fluxes to the groundwater. In: J Steenvoorden, F Claessen and **J** Willems (eds). Agricultural Effects on Ground and Surface Waters: Research at the Edge of Science and Society, Wageningen. IAHS Press, Wallingford, pp. 261-265.

Tate KR, DJ Ross, BJ O'Brien and FM Kelliher. 1993. Carbon storage and turnover, and respiratory activity, in the litter and soil of an old-growth southern beech (Nothofagus) forest. *Soil Biol Biochem* 25: 1601-1612.

Turrion MB, JF Gallardo, L Haumaier, MI Gonzalez and W Zech. 2001. ^{31}P-NMR characterization of phosphorus fractions in natural and fertilized forest soils. *Ann Forest Sci* 58: 89-98.

Ugolini FC, MG Stoner and DJ Marrett. 1987. Arctic pedogenesis: 1. Evidence for contemporary podzolization. *Soil Sci* 144: 90-100.

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

Yusran FH. 2008. Existing versus added organic matter in relation to phosphorus availability on lateritic soils. *J Trop Soils* 13: 23-34.

Zogg GP, DR Zak, DB Ringelberg, NW MacDonald, KS Pregitzer and DC White. 1997. Composition and functional shifts in microbial communities related to soil warming. *Soil Sci Soc Am J* 61: 475-481.