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A glasshouse evaluation of the comparative effects of organic amendments, lime and phosphate on alleviation of Al toxicity and P deficiency in an Oxisol

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SUMMARY

The effects of additions of four organic amendments to an Oxisol on soil pH, exchangeable and soil solution Al, extractable P and maize growth were compared with those of lime and P in a glasshouse experiment. The organic amendments were: grass residues, household compost, filter cake (a waste product of sugar mills) and layer poultry manure and they were added at a rate equivalent to 20 t/ha with or without the addition of either lime (equivalent to 0, 5 or 10 t/ha) or P (equivalent to 0, 10 or 50 kg/ha). Lime applications to the control (unamended) treatment resulted in a marked reduction in exchangeable Al, and concentrations of total (Al_T) and monomeric (Al_{mono}) Al in soil solution and the proportion of Al_T present as Al_{mono}. In unlimed soils, amendment additions increased pH and decreased exchangeable Al in the order: poultry manure > filter cake > household compost > grass residues > control. The addition of all the organic amendments increased soil pH and reduced Al_T and Al_{mono} to low concentrations regardless of whether lime was applied or not. As a result, there was no yield response to applied lime in any of the amended treatments. Olsen-extractable P concentrations in soils followed the order: poultry manure > filter cake > household compost > grass residues > control and there was no yield response to applied P for the poultry manure and filter cake treatments. The decrease in adsorption of subsequently added P induced by additions of organic amendments followed the order: poultry manure > household compost > filter cake > grass residues. It was concluded that the addition of organic amendments to acid soils is a practicable way of liming them and reducing the potential for Al toxicity and it can also reduce fertilizer P requirements.

INTRODUCTION

Acid soil infertility is a major limitation to crop production on highly weathered and leached soils in both tropical and temperate regions of the world (Von Uexküll & Mutert 1995). Aluminium toxicity is usually the major growth-limiting factor for crop production in acid soils (Foy 1992). Highly weathered acid soils are also often P deficient and they contain large amounts of Al and Fe oxides which have the ability to adsorb P onto their surfaces. Thus, much of the added P is 'fixed' and not readily available for crop use. In commercial agriculture, these problems are commonly corrected by heavy applications of lime and soluble P fertilizer. Due to economic and logistic constraints, fertilizer P and lime are often not available to semi-subsistence farmers and practicable alternatives need to be sought.

Research has shown that additions of green manures, animal wastes and composts to acid soils can reduce Al toxicity and increase crop yields (Hoyt & Turner 1975; Hue & Amien 1989; Berek *et al.* 1995). An increase in soil pH and/or complexation of soil solution Al by decomposition products of organic residues (e.g. organic acid anions and soluble humic material) have been implicated as the main factors in such Al detoxification (Haynes & Mokolobate 2001).

Additions of organic residues have also been shown to increase P uptake and dry matter yields of crops in P-deficient soils (Hue *et al.* 1994). Part of this effect is

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undoubtedly due to the release of P along with other nutrients from the residues. However, it is also thought that residue-derived organic anions may become adsorbed onto surfaces of Fe and Al oxides thus blocking adsorption of subsequently added P and increasing its plant availability (Iyamuremye & Dick 1996).

The purpose of the glasshouse study reported was to compare applications of lime and P with additions of readily available organic materials, on the availability of P and other nutrients, solubility of Al, plant growth and nutrient uptake in an Oxisol.

MATERIALS AND METHODS

The soil was collected from the Bergville district of the KwaZulu–Natal midlands of South Africa from a site that had not received fertilizer or lime. The soil was classified as a Hutton form, Farmingham series (Soil Classification Working Group 1991) (Rhodic Ferralsol, FAO). The soil had a clay content of 42% and its mineralogy was dominated by kaolinite plus halloysite and there were also appreciable amounts of crystalline sesquioxides, gibbsite and interlayered chlorite present.

The organic amendments used were: ground (<0·5 mm) native grassland vegetation (mainly *Digitaria sanguinatis* L. and *Tristachya leucothrix* L.), sieved (<2 mm) household compost, sieved filter cake obtained from a commercial sugar mill and sieved layer poultry manure obtained from a commercial egg producer. The household compost was derived from home waste (e.g. vegetable peelings, unwanted leaves, fruit skins, egg shells, tea leaves etc.) and also some garden waste (e.g. remains of vegetable crops, stalks and thin prunings). Filter cake (also known as filter press mud) is an organic waste product of sugar mills. In order to clarify the juice produced following its extraction by milling the cane, lime is added to the heated juice, and the suspended organic material is then filtered in filter presses and collected as a solid cake. The above organic residues were chosen because large amounts of filter cake are available from sugar mills, layer poultry (for egg production) is important in both commercial and small scale farming, grass residues are available on large tracts of undeveloped land and composting of household wastes is a sound recycling strategy.

The research consisted of two main experiments. In the first there were five main treatments: (i) control, (ii) household compost (H. compost), (iii) grass residues (G. residues), (iv) poultry manure (P. manure) and (v) filter cake (F. cake) which were applied at a rate of 20 mg/g (equivalent to 20 t/ha). To these treatments, three rates of lime 0, 5 and 10 mg/g (equivalent to 5 and 10 t/ha) were applied to give a total of 15 treatments. For the second experiment, the same five organic residues were applied and to these three rates of P [as $Ca(H_2PO_4)_2$] 0, 10 and 50 μg P/g (equivalent to 0, 10, and 50 kg P/ha) were applied to give another 15 treatments.

For both experiments there were six replications of each treatment. The organic amendments were mixed with bulk samples of the soil. Subsamples (1 kg) of these treatments were then taken and appropriate amounts of lime ($CaCO_3$) or $Ca(H_2PO_4)$ were mixed with the soil and the samples were then placed in plastic pots. A basal fertilizer application was applied to all treatments of N, K, Mg, Mn, Mo, Zn, Cu and B at rates equivalent to 200, 200, 100, 25, 10, 15, 15 and 10 kg/ha respectively. The pots of four replicates were sown with seven maize seeds (*Zea mays* L. cv Silver King) and later thinned to four per pot. The other two replicates remained unplanted. Pots were arranged in a randomized complete block design and maintained at 70% of water-holding capacity (watered every 2 days to weight) in a glasshouse with air temperature held between 20 and 25 °C. Plants were grown for 6 weeks. Above-ground herbage was harvested, oven dried, weighed and ground (<0·5 mm). Twenty-four hours prior to harvest the unplanted pots were rewetted to 100% water-holding capacity and after that period the soil solution was extracted by centrifugation (Elkhatib *et al.* 1987). Another sample was air-dried and sieved (<2 mm) and used for other chemical analysis.

Air-dried, ground (<0·5 mm) samples of the organic residues were analysed for total N by Kjeldahl digestion with colorimetric determination of liberated ammonium (Foster 1995) and organic C by the Walkley & Black dichromate oxidation procedure (Blakemore *et al.* 1972). Samples were digested in nitric and perchloric acids and the P content of digests was measured by the molybdenum blue method (John 1970) and the Ca, Mg, K, Na and Al contents by atomic absorption spectrophotometry. The pH of organic residues was measured in 0·002 M $CaCl_2$ and their proton consumption capacities were estimated by slowly titrating them from their natural pH values down to pH 4·0 with 0·05 M H_2SO_4 (Wong *et al.* 1998). The $CaCO_3$ content of amendments was measured by the titrimetric method of Bundy & Bremner (1972) and ash alkalinity was measured as described by Slattery *et al.* (1991).

Monomeric Al (Al_{mono}) in soil solution was measured in the filtrate (0·05 μm millipore filter extract) by the pyrocatechol violet (PCV) method (Kerven *et al.* 1989) and total soluble Al (Al_T) was measured by a modified PCV method using $LaCl_3$–Fe reagent after passing the solution through a 0·22 μm filter (Menzies *et al.* 1992). It is accepted here that the PCV method for measuring Al_{mono} measures monomeric Al plus a small amount of Al present in soluble Al-organic matter complexes (Parfitt *et al.* 1995). The pH and electrical conductivity of soil solutions was also measured.

Soil pH was measured in a 1:2·5 soil:solution ratio (in both water and 1 M KCl) using a glass electrode. Exchangeable cations were extracted with 1 M ammonium acetate (1:50 soil extractant ratio for 2 h) and the filtered extract was analysed for Ca, Mg, K and Na by atomic absorption spectrophotometry. Exchangeable Al was extracted with 1 M KCl (1:2·5 soil:extractant ratio for 1 h) and Al was measured by atomic absorption spectrophotometry. Available P was extracted from soils using 0·5 M $NaHCO_3$ (Olsen *et al.* 1954) and P in the extract was measured by the molybdenum blue method.

Phosphate adsorption isotherms were constructed on samples of control soils (no added lime or P) that had received organic amendments. Duplicate samples of soil (1 g) were placed into centrifuge tubes together with 15 ml of 0·02 M $CaCl_2$ solution containing a few drops of toluene to limit microbial growth. After the addition of an appropriate quantity of P (as KH_2PO_4 solution) the solutions were made up to 30 ml with distilled water to give a final $CaCl_2$ concentration of 0·01 M. The tubes were shaken for 72 h at 20 °C and then centrifuged. The P concentration in the filtered supernatant solution was analysed by the molybdenum blue method and adsorbed P was calculated by difference.

Ground plant samples were analysed for N, P, K, Ca, Mg, Al and Mn by methods described previously for the organic residues.

The statistical significance of experimental treatments was determined by subjecting the data to analysis of variance using the Genstat 5 package.

RESULTS AND DISCUSSION

The soil used in the current study was an acidic, P-deficient Oxisol typical of those farmed by small-scale farmers in the midlands of KwaZulu–Natal. It had the following properties: $pH_{(water)}=4{\cdot}2$, $pH_{(KCl)}=4{\cdot}0$, organic C = 22 g/kg, Olsen P = 7 mg/kg and exchangeable Ca, Mg, K, Na and Al of 4·0, 1·1, 1·9, 0·3 and 13 $mmol_c$/kg respectively.

An increase in soil pH induced by additions of organic residues was clearly evident in unlimed soils (Fig. 1) and this caused a decrease in the solubility of soil Al. Thus the trend for soil solution pH was: control < grass residues and household compost < filter cake < poultry manure while the trend for exchangeable Al was the reverse (Fig. 2). Trends for changes in $pH_{(water)}$ (Table 1) and $pH_{(KCl)}$ (data not presented) with treatment were similar to those measured in soil solution. Some relevant properties of the organic residues are presented in Table 2. Poultry manure and filter cake had notably high pH values which are a reflection of their relatively high $CaCO_3$ content. Proton consumption capacity and ash alkalinity (a measure of organic acid anion content) followed the order: poultry manure > filter cake > household compost > grass residues.

The reasons for the increases in soil pH induced by these residues have been discussed in detail elsewhere (Mokolobate & Haynes 2002) and differ for the different organic residues. The dominant mechanisms are thought to be decarboxylation of organic acid anions during decomposition of plant material (Yan *et al.* 1996; Tang *et al.* 1999) for the grass residues, the high proton consumption capacity of humic material present in household compost (Wong *et al.* 1998) and the high $CaCO_3$ content of filter cake and poultry manure. Increases in soil pH following applications of poultry manure (Hue 1992; Cooper & Warman 1997), composts (Mays *et al.* 1973; Terman *et al.* 1973) and crop residues (Hue & Amien 1989; Tang *et al.* 1999) have been previously reported. The liming effect of filter cake has not been stressed by other workers (Moberly & Meyer 1978; Ng Kee Kwong & Deville 1988) but is clearly an important property in acid soils.

Surprisingly, in the liming experiment, the pattern of change in Al_T and Al_{mono} with treatment (Fig. 1) did not reflect that for exchangeable Al (Fig. 2). That is, for the control treatment, liming greatly decreased exchangeable Al, Al_T and Al_{mono}. By contrast, for the grass residue, household compost and filter cake treatments, although liming markedly reduced exchangeable Al concentrations, it had no significant effect on either Al_T or Al_{mono} (Figs 1 and 2). Thus, where these organic residues had been applied to the soil, concentrations of exchangeable Al did not appear to be the main factor determining concentrations of Al in soil solution. The most likely explanation for this is that Al was complexed by the added organic matter and its decomposition products, in both the solid and solution phases (Haynes & Mokolobate 2001). That is, soil solution concentrations of Al are more influenced by the presence of both soluble and insoluble organic ligands than by the buffering background levels of exchangeable Al. The result of this was that concentrations of Al_{mono} were low in all treatments receiving organic amendments irrespective of whether lime was applied or not.

Surprisingly, applications of P did not significantly influence concentrations of exchangeable Al or Al_T and Al_{mono} in soil solution (Figs 1 and 2). Often, P applications can reduce Al solubility through the formation of insoluble aluminium phosphates (Haynes 1984). Perhaps the relatively high P adsorption capacity of the soil and the low initial concentrations of available P (Fig. 2) resulted in added P being rapidly adsorbed to the surfaces of soil colloids rather than it being involved in precipitation reactions.

For limed soil samples, both the household compost and grass residue treatments tended to maintain higher concentrations of Al_T in soil solution than the

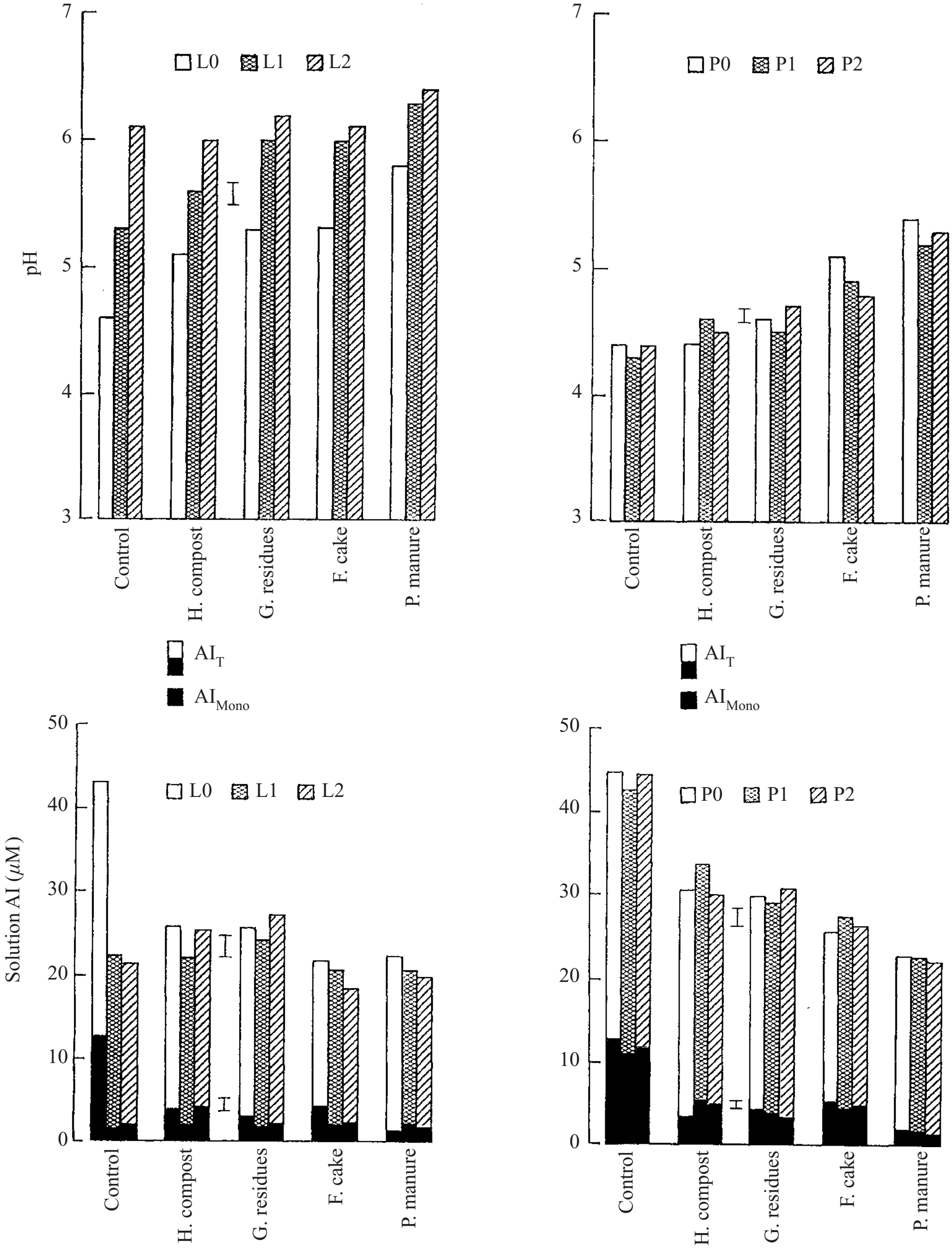

Fig. 1. Effect of incubation of organic residues with an acid soil for 6 weeks with the addition of either lime or P at three rates on pH, and on concentrations of total (Al$_T$) and monomeric (Al$_{mono}$) in soil solution. $L_0=0$, $L_1=5$, $L_2=10$ mg lime/g. $P_0=0$, $P_1=10$, $P_2=50$ μg P/kg. Vertical bars indicate S.E. (D.F. = 15). Abbreviations as in text.

control treatments (Fig. 1). Several other workers have noted that Al$_T$ in soil solution can be unaffected or even increased during the decomposition of organic residues (Berek *et al.* 1995; Slattery & Morrison 1995). In such cases it is thought that the large amounts of soluble organic matter present in solution complex with Al and maintain it in the solution phase. In addition, a decrease in the Al^{3+} activity in

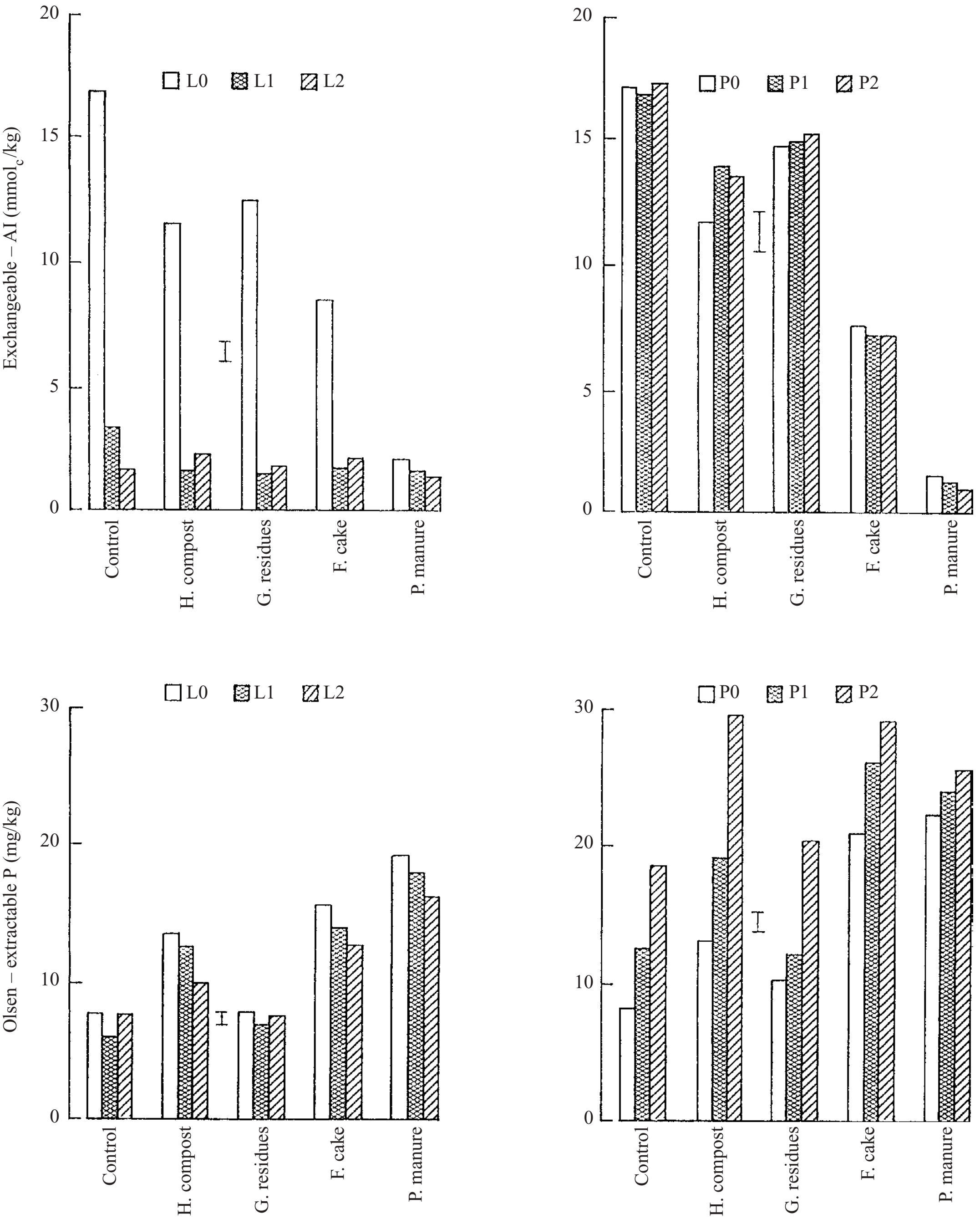

Fig. 2. Effect of incubation of organic residues with an acid soil for 6 weeks with the addition of either lime or P at three rates on concentrations of exchangeable Al and Olsen-extractable P. $L_0=0$, $L_1=5$, $L_2=10$ mg lime/g. $P_0=0$, $P_1=10$, $P_2=50$ µg P/kg. Vertical bars indicate S.E. (D.F. = 15). Abbreviations as in text.

Table 1. *Effect of incubation of organic residues with an acid soil for 6 weeks (unlimed treatments) on pH_{water}, electrical conductivity in soil solution and exchangeable cation content*

Treatment	$pH_{(water)}$	Electrical conductivity (mS/cm)	Exchangeable cations ($mmol_c$/kg) Ca	Mg	K	Na
Control	4·2	1·9	9·6	6·7	5·1	2·3
Household compost	4·4	2·7	14·5	8·3	6·2	2·5
Grass residues	4·3	1·8	9·8	8·8	6·9	2·4
Filter cake	4·7	2·2	19·2	8·1	5·2	2·4
Poultry manure	5·6	3·3	31·4	11·2	8·7	3·0
S.E. (D.F. = 5)	0·1	0·2	2·2	0·6	0·4	0·2

Table 2. *Some selected chemical properties of the organic residues used*

Organic residue	Organic C (g/kg)	pH	$CaCO_3$ content (%)	Proton consumption capacity ($cmol_c$/kg)	Ash alkalinity ($cmol_c$/kg)	Nutrient content (g/kg) N	P	K	Ca	Mg	Na
Household compost	231	6·7	1·5	57	137	37	11	14	32	3·9	1·0
Grass residues	669	5·8	—	23	58	40	5·8	14	7·1	2·1	1·3
Filter cake	103	8·2	11·9	195	235	12	11	8·5	60	5·5	0·6
Poultry manure	239	7·8	25·0	280	375	63	21	20	77	5·7	2·6

soil solution due to complexation by soluble organic matter would result in movement of exchangeable Al^{3+} into solution by exchange reactions and, in the long term, to more dissolution of Al-containing minerals (e.g. gibbsite and amorphous hydroxy-Al oxides) and thus an increase in Al_T in soil solution.

The organic amendments contained significant quantities of P and this was released during their decomposition. Released inorganic P will have been rapidly adsorbed onto soil colloid surfaces (resulting in an increase in Olsen P; Fig. 2) thus increasing the proportion of P adsorption sites occupied by orthophosphate. As a result, P adsorption capacity of the soil was decreased with respect to subsequently added P (Fig. 3). Indeed, P adsorption isotherms followed the order: control > grass residues > filter cake > household compost > poultry manure. Nevertheless, even though Olsen P concentrations were greater for filter cake than household compost (Fig. 2), additions of household compost actually reduced P adsorption capacity to a greater degree than filter cake (Fig. 3). The reason for this is probably that humic substances from the household compost were specifically adsorbed thus blocking P adsorption sites and decreasing P adsorption capacity (Iyamuremye & Dick 1996). The critical Olsen P concentration for maize is between 10 and 15 mg/kg (Kamprath & Watson 1980) so additions of poultry manure, filter cake and household compost would have ensured P was not limiting growth even where fertilizer P was not applied.

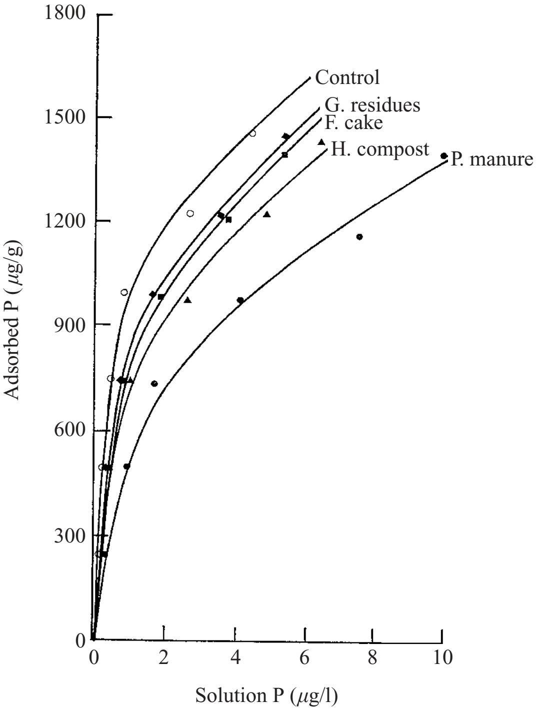

Fig. 3. Phosphate adsorption isotherms for soils after incubation with organic residues for 6 weeks. Abbreviations as in text.

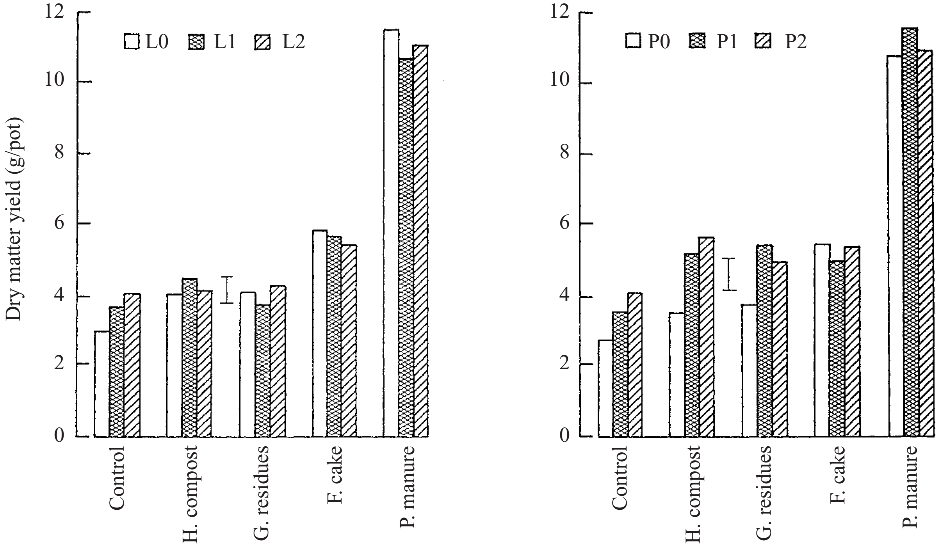

Fig. 4. Effect of incubation of organic residues with an acid soil for 6 weeks with the addition of either lime or P at three rates on dry matter yields of maize plants grown over a subsequent 6 week period. $L_0 = 0$, $L_1 = 5$, $L_2 = 10$ mg lime/g. $P_0 = 0$, $P_1 = 10$, $P_2 = 50$ μg P/kg. Vertical bars indicate S.E. (D.F. = 45). Abbreviations as in text.

In the control treatments, liming, as expected, caused precipitation of exchangeable and soluble Al as hydroxy-Al species, alleviation of Al toxicity and a positive yield response in maize (Fig. 4). The lack of yield response to applied lime in any of the soils amended with organic materials (Fig. 4) reflects the fact that in these treatments liming had no effect on concentrations of Al_T and more particularly Al_{mono} (Fig. 1). Indeed, it is the activity of Al^{3+} and/or monomeric hydroxy-Al species in solution that is toxic to plants (Kochian 1995). Measured values of Al_{mono} of about 12–15 μM in the control treatment were reduced to below 5 μM in limed soils and/or those amended with organic residues (Fig. 1) and these latter concentrations are small and unlikely to limit maize growth. For example, in soil solution culture experiments, Harper *et al.* (1995) showed that 19 μM Al_{mono} inhibited root growth of maize while 3 μM did not. Diatloff *et al.* (1998) showed that 24–27 μM inhibited maize root growth while 8 μM did not. Thus, it is concluded that lime, or any of the organic amendments used, reduced Al_{mono} to non-phytotoxic concentrations.

In the present study, the most pronounced yield increase was to the application of poultry manure which occurred irrespective of whether lime or P was added or not (Fig. 4). Analysis of the nutrient concentration of maize tissues did not, however, give a clear indication of the reason for this large yield response (Table 3). That is, none of the nutrients were present in notably higher concentrations in plants from poultry manure than from other treatments (concentrations of tissue Mn, Zn and Mg were, in fact, lower). Visual observations suggested that the yield response to poultry manure became obvious only in the last few weeks of maize growth. A more prolonged release of nutrients in this treatment (particularly N) may have enabled plants to continue growing at a greater rate than that for the other treatments. Indeed, the fact that tissue nutrient concentrations were similar in the poultry manure to other treatments indicates that nutrient uptake was, in fact, much greater (since yields were much greater in the poultry manure treatment).

It is evident that additions of organic residues can have a liming effect and can greatly reduce concentrations of exchangeable and soil solution Al. Because of their nutrient content their application also improves soil nutrient status. All the amendments used had a significant N, K, Ca and Mg content and increases in exchangeable Ca, Mg and K concentrations were observed (Table 1). In particular, their addition improved the P status of the soil (Fig. 2) and reduced adsorption of subsequently added P (Fig. 3). Electrical conductivity in soil solution and exchangeable Na^+ concentrations were both raised significantly by poultry manure applications (Table 1). These increases were, however, small and they had no detrimental effect on plant growth.

Highly weathered acid soils predominate in South East Asia, Africa and central South America where much of the agriculture practiced is semi-subsistence farming. Aluminium toxicity and P deficiency are often limiting factors to crop production in such soils

Table 3. *Effect of incubation of organic residues with an acid soil, with the addition of three rates of lime, on nutrient content of tops of maize plants grown for 6 weeks*

Treatment	N	P	K	Ca	Mg	Al	Fe	Cu	Mn	Zn
			(g/kg)					(mg/kg)		
Control										
L_0*	9·1	11·0	36·0	5·9	3·1	46·0	182·0	11·0	292·0	31·0
L_1	6·6	8·7	35·0	11·0	3·1	42·0	228·0	12·0	108·0	24·0
L_2	6·5	8·8	34·0	13·0	2·9	37·0	145·0	11·0	98·0	17·0
Household compost										
L_0	5·9	12·0	42·0	5·9	3·1	67·0	178·0	10·0	229·0	30·0
L_1	6·8	12·0	41·0	10·0	2·6	65·0	175·0	12·0	93·0	20·0
L_2	6·8	10·0	36·0	11·0	2·5	43·0	211·0	9·7	82·0	17·0
Grass residues										
L_0	6·4	13·0	44·0	5·6	2·5	44·0	148·0	12·0	258·0	28·0
L_1	7·0	9·4	44·0	8·0	2·3	42·0	158·0	9·7	99·0	21·0
L_2	7·3	8·6	36·0	10·0	2·0	44·0	176·0	11·0	85·0	17·0
Filter cake										
L_0	5·2	14·0	29·0	7·9	3·4	37·0	166·0	9·8	185·0	22·0
L_1	7·3	13·0	31·0	10·0	3·0	41·0	168·0	10·0	108·0	17·0
L_2	5·5	11·0	29·0	13·0	2·8	48·0	207·0	11·0	90·0	14·0
Poultry manure										
L_0	8·4	9·3	37·0	6·3	2·4	38·0	149·0	9·6	118·0	24·0
L_1	7·7	13·0	33·0	7·5	2·0	42·0	147·0	9·3	74·0	16·0
L_2	7·6	13·0	33·0	6·9	1·9	45·0	190·0	12·0	73·0	14·0
S.E. (D.F. = 15)	1·1	2·0	2·8	1·1	0·3	5·1	28·0	1·0	14·8	2·1

* Rates of lime applied were $L_0 = 0$, $L_1 = 5$, $L_2 = 10$ mg lime/g.

and the use of organic residues is an intriguing alternative to the use of lime and P fertilizers which are expensive inputs for semi-subsistence farmers. It is interesting to note that many such farmers routinely use animal manures to fertilize their crops and this may well be having a liming effect that is, at present, unknown. The next step in this research is to initiate field experiments to determine the relative liming effects of various types of organic residues, the most appropriate timing of their application and the best techniques for applying them. For example, amendments would not necessarily be applied over the entire field but in bands down the plant rows prior to sowing so the rate of application used in this study (equivalent to 20 t/ha) would certainly not be impracticable.

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