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Soil management effects on phosphorus sorption and external P requirement in oxisols of Malawi

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Oxisols are one of the major soils of Malawi and they are high in P sorption. Conservation agriculture has been practiced on this soil for some years now but soil management effects on P sorption and external P requirement (EPR) of Oxisols in Malawi have not, however, been determined. Soil management effects on P sorption and EPR of Oxisols in Malawi were therefore determined in the present study. The effects studied were conventional tillage (CT), no-tillage (NT) and crop rotation (CR). The soils differed considerably in their sorption characteristics, with the sorption maxima ranging from 413 to 345 mg P kg⁻¹. Differences in sorption maxima and affinity due to soil management effects were statistically significantly ($P \leq 0.05$). The sorption affinity (b) values ranged from 0.48 to 0.72 dm³ mg⁻¹ and differences due to soil management effects were statistically significant ($P \leq 0.05$) only between conventional tillage (CT) and no tillage (NT) or crop rotation (CR). The sorption affinity due to NT was not statistically significant from that of CR. The b values were the highest in soils that had been subjected to CT.

Key words: Oxisols, soil management effects, sorption affinity, sorption maxima, external P requirement.

INTRODUCTION

It has been observed that due to an increasing demand of agricultural production for phosphorus (P) and the fact that the peak in global P production may soon occur, P is now receiving more attention than ever before as a non-renewable resource (Cordell et al., 2009; Gilbert, 2009). Soils serve as the principal reservoir of P in terrestrial systems. They contain P ranging from 35 to 5,300 mg kg⁻¹, with a median concentration of 800 mg kg⁻¹ (Bowen, 1979; Sparks, 2003). In soils, P exists in various chemical forms including inorganic and organic P forms. These P forms differ in their behaviour and fate in soils (Hansen et al., 2004; Turner et al., 2007).

Inorganic P usually accounts for 35 to 70% of total P in soil. Primary P minerals including apatites, strengite, and

variscite are very stable, and the release of available P from these minerals by weathering is generally too slow to meet the demand of annual crops through direct application of phosphate rocks. In contrast, secondary P minerals including calcium (Ca), iron (Fe), and aluminium (Al) phosphates vary in their dissolution rates, depending on size of mineral particles and soil pH (Pierzynski et al., 2005; Oelkers and Valsami-Jones, 2008). With decreasing soil pH, solubility of Fe and Al phosphates decreases while the solubility of Ca phosphate decreases with increasing soil pH except for pH values above 8 (Hinsinger, 2001).

The strong affinity of phosphate ions for the solid phase of soils causes P to be very low in its effective

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concentration in soil solutions where it is in dynamic equilibrium with the solid phase. In highly weathered soils of the tropics and subtropics, limited availability of soil P is often the main constraint to plant growth. In Malawi, the fertilisers smallholder farmers add to their soils invariably carry, among other essential elements, nitrogen and phosphorus in order to optimise crop production. For maize (*Zea mays* L.) production, P fertilisation is usually aimed at maintaining an effective concentration of 0.02 mg P kg⁻¹. Phosphate ions introduced into soil solutions, which are not absorbed by the growing plant or immobilized by soil microbes, however, are subject to various chemical reactions. These include precipitation and dissolution (mineral equilibria or pseudo-equilibria) and sorption and desorption (interactions between P in solution and soil solid phases).

The kinetics of dissolution and precipitation of P minerals, such as variscite (AlPO₄·2H₂O) and strengite (FePO₄·2H₂O) that form and become stable in acid soils or octocalcium phosphate [Ca₈H(PO₄)_{6.5}H₂O] and hydroxyapatite [Ca₅(PO₄)₃OH] that form and become stable in alkaline soils govern the effective concentration of phosphate ions in soil solution. The solubilities of the aluminium-bound phosphate (Al-P) mineral and iron-bound phosphate (Fe-P) mineral decrease with increasing acidity whereas the calcium-bound phosphate (Ca-P) minerals decrease with decreasing hydrogen ion (H⁺) concentration.

The P concentration in soil solution is also influenced by sorption and desorption. The combined processes of desorption and dissolution influence the bioavailability of phosphate ions in soil solutions. Both desorption and precipitation occur in response to disequilibria established in solution by removal of P from solution (disequilibria desorption); or in response to the action of ligands exchanging with phosphate or dissolving phosphate-bearing compounds (ligand desorption). Bioavailable desorbable P is commonly indexed by extracting a portion of the labile pool of P with chemical extractants, such as Bray 1, Mehlich 1 or 3, or Olsen's Solution (Ziadi et al., 2001). Soil P tests can, however, be used as indices of P availability, able to accurately predict the amount of P that is available for plant uptake, only after they have been subjected to, and selected from, correlation and calibration studies using laboratory, greenhouse and field experimental data. Because soil tests serve as an index to P bioavailability and do not define the pattern of P release, or the influence of P desorption on the soil solution concentration, they have limited utility in the mechanistic modelling of P bioavailability and uptake by plants.

Whereas the combined processes of desorption and dissolution do generally influence the bioavailability of phosphate ions in soil solutions, in highly weathered soils, such as those that occur in the tropics, it is the degree of phosphate sorption that largely controls the effective concentration and therefore P bioavailability of

phosphate ions in soil solutions. Phosphate (P) adsorption is the process in which the ions are held on the active sites of the soil particle surfaces. The amount of P adsorbed by soil increases as the effective concentration of phosphate ions in solution increases and vice versa. Adsorption affects the fate of P-source and the availability of phosphate to plants. Adsorbed or precipitated inorganic phosphate undergoes desorption or dissolution reactions when moving from the solid to the solution phase.

The relationship between P sorbed on the solid phase and P in the solution phase defines what is known as adsorption isotherm. Adsorption isotherm can be described as the equilibrium relationship between the amounts of adsorbed and dissolved species of phosphate at constant temperature in quantitative terms. The P adsorption isotherm is a useful, descriptive characteristic of soil that provides information on the ability of the soil to hold P in reserve and release it into solution as the phosphate ions are removed from the solution. Phosphorus sorption relationships are commonly used in the determination of external phosphorus requirement (EPR) of crops. The EPR of crops has been defined as the concentration of P in solution known to be non-limiting to plant growth (Henry and Smith, 2004). For most crops, the amount of P in equilibrium with 0.2 mg P dm⁻³ (P_{0.2}) has been shown to be the threshold over which no response to P is observed (Iyamuremye et al., 1996; Nziguheba et al., 1998). The P requirements, estimated in this manner, aim at building up the status of soil phosphorus by a single application to a level which, thereafter, only requires maintenance application to replenish losses due to plant uptake, removal by erosion or continuing slow reactions between phosphate and soil (Henry and Smith, 2003).

Most of the upland soils (Oxisols and Ultisols) in Malawi are dominated by the poorly buffered 1:1 kaolinite and halloysite and oxides of iron and aluminium, reflecting that the soils are highly weathered and leached (Maida, 1973; Mwandemere and Robertson, 1975; Ntokotha, 1974). The poorly buffered soils account for over 40% of soils in Malawi. Mughogho (1975) conducted P sorption studies on Oxisols and Ultisols collected from several sites in Malawi. The Oxisols have since then been subjected to conventional tillage (CT). The extent to which CR influences P sorption and EPR characteristics of the Oxisols has, however, not been determined in Malawi. The main objective of the present investigations therefore was to determine the capacity of the Oxisols to sorb P and the EPR of crops after they have been subjected to four years of crop rotation.

MATERIALS AND METHODS

Description of the experimental site and soil sampling

This study was carried out in Nkhhotakota district which lies between

33°22' east and 34°10' east and between 13°20' south and 3°40' south in the central part of Malawi. It is located at just 82 km away from Lilongwe University of Agriculture and Natural Resources. Topographically, it is divided into two parts: the eastern part is predominantly hilly while the western part is low. The hilly eastern part is well drained by small streams which flow into Lake Malawi. The average annual rainfall ranges from 750 to 1,000 mm and the temperature is within the range of 15° to 35°. Soil samples used in the present study were collected from an experimental site where soils had been subjected to no-tillage (NT) and to crop rotation (CR) for three years. Twelve representative top soils (0 to 20 cm) were randomly collected in a zigzag manner from the site, air-dried, and ground to pass through a 2-mm sieve.

Soil characterization

The soils were analyzed for pH in a 1:2.5 soil to water slurry using a pH electrode as outlined by Blakemore et al. (1987), particle size distribution using the Bouyoucos hydrometer method (Day, 1965) as described by Anderson and Ingram (1993). The soil organic carbon contents were determined using the potassium dichromate ($K_2Cr_2O_7$) oxidation method of Walkley and Black (1934) as described by Anderson and Ingram (1993) by multiplying the total soil organic carbon with 1.724. Total nitrogen was determined using the Kjeldhal wet oxidation process as described by Anderson and Ingram (1993).

Total P was estimated following wet digestion with H_2O_2/H_2SO_4 (Okalebo et al., 2002), while P in the clear extracts was determined colorimetrically by the ascorbic acid method (Murphy and Riley, 1962) on a Perkin Elmer Lambda 25 UV/VIS spectrometer. Exchangeable Ca^{2+} , Mg^{2+} , and K^+ were extracted using Mehlich-3 method (Mehlich, 1984) and determined by atomic absorption spectrophotometer. Exchangeable acidity ($Al^{3+} + H^+$) was extracted with 1.0 M KCl and titrated with 0.05 M NaOH (Okalebo et al., 2002).

Phosphate sorption isotherms

Two grams of air-dried and ground (<2 mm) soil samples were weighed in triplicates into 50 ml centrifuge tubes and suspended in 30 ml of 0.01 M $CaCl_2$ of supporting electrolyte containing various concentration of P as KH_2PO_4 to give 0, 100, 200, 300, 400, and 500 P mg kg^{-1} of soil for six days at a room temperature. Three drops of toluene were added to minimize microbial activity. Suspensions were shaken twice daily for 30 min and at the end of the sixth day, they were centrifuged at 10,000 rev min^{-1} and filtered through Whatman No. 42 filter paper. Phosphorus content in the clear supernatant solution was determined colorimetrically by the ascorbic acid method (Murphy and Riley, 1962) on a Perkin Elmer Lambda 25 UV/VIS spectrometer.

The amount of P remaining in solution was taken to be the equilibrium concentration (C) and expressed as mg P dm^{-3} . The amount of P sorbed (mg P kg^{-1} soil) was estimated as the difference between equilibrium P concentration and initial P added. One of the models that quantitatively describe adsorption isotherm is that of Langmuir (Pant and Reddy, 2001; Essington, 2003; Dossa et al., 2008). The sorption data were fitted to the following linearized form of the Langmuir equation:

$$\frac{C}{S} = \frac{1}{S_{max} \times b} + \frac{C}{S_{max}}$$

Where C is the P equilibrium P concentration (mg dm^{-3}), S is the total amount of adsorbate (adsorbed P) taken up per unit mass of adsorbent (mg kg^{-1}) = adsorption maximum mg kg^{-1} . B is a constant

related to the bonding energy of the soil for P or affinity constant (Uzoho and Oti, 2005).

A plot of $C/(x/m)$ versus C gave a straight line equation with slope as $1/b$ and an intercept as $1/kb$

Soil external P requirements

Soil external P requirements of crops were determined by substituting the desired P concentration (0.2 mg P dm^{-3}) into the following Langmuir equation (Dodor and Oya, 2000):

$$S = \frac{S_{max} \times bC}{1 + bC}$$

Where S, S_{max} , b and C are as defined as stated earlier.

Statistical analysis

The relationship between P sorption parameters and P sorbed at equilibrium with 0.2 mg P dm^{-3} with selected soil chemical properties was determined using simple regressions and correlations, and tested for significance at 0.01 and 0.05 probability levels using the 16th edition of GenStat statistical software. The contribution of soil properties to sorption parameters was examined using the stepwise model-building procedure. The differences in P sorption among the treatments within site and across sites was analysed using ANOVA and tested at significant level 0.05.

RESULTS AND DISCUSSION

Soil organic matter

Table 1 shows the selected properties of the Oxisols. The properties of the soils varied with soil management effects. The increase in soil organic matter (OM) contents observed in soils subjected to CR and NT was consistent with conclusions of Rasmussen (1999) and During et al. (2002) which attributed an increase in organic matter contents of the topsoil subjected to annual no-tillage to plant residues left on the soil surface. Lal (1997b) also observed soil organic carbon (SOC) to be significantly higher in the soil subjected to NT than the one that was under conventional tillage (CT) treatment.

Ali et al. (2006), however, observed OM and other soil variables such as N, P, K, Ca and Mg to have the lowest values recorded in CT plots. This finding was attributed to the inversion of topsoil during ploughing, which was postulated to have shifted less fertile subsoil to the surface, and to possible leaching. Busari and Salako (2013) observed in South Western Nigeria that soil, the soil organic C (SOC) and the effective cation exchange capacity (CEC) were significantly higher at the end of a two-year study under NT than under CT. The present study also showed organic matter contents to be the lowest in the soil that had been subjected to CT (Table 1). In addition to the factors that have been cited by earlier workers referred to earlier as possible causes for the low organic matter contents in the soil that was under CT, the loosening of the soil caused by CT and the

Table 1. Selected soil characteristics.

Soil properties	Treatment			Grand mean
	CR	NT	CT	
OM (g kg ⁻¹)	17.0	11.2	3.4	10.6
pH (water)	5.1	4.9	4.7	4.9
Al _(ex) (cmol _c kg ⁻¹)	3.3	2.6	7.9	4.6
N (%)	1.4	1.6	1.5	1.5
K (cmol _c kg ⁻¹)	0.13	0.10	0.17	0.13
Mg (cmol _c kg ⁻¹)	0.31	0.36	0.42	0.36
Ca (cmol _c kg ⁻¹)	4.97	6.84	10.56	7.50
Total P (mg kg ⁻¹)	126.9	123.0	23.8	91.2

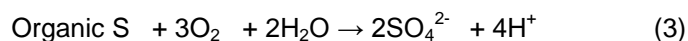
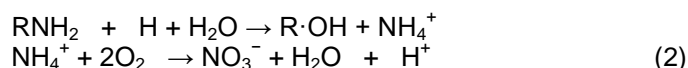
CR: Crop rotation; NT: no tillage; CT: conventional tillage.

resultant improvement in soil aeration may have also created a soil ambient which, under high soil temperatures, might have been favourable for increased microbial activities and OM biodegradation leading to the observed low OM values.

Soil pH

The soil that was under CT treatment had the lowest pH value (Table 1). Some of the earlier workers, for example Rasmussen (1999) observed no effects that could be attributed to tillage systems while other findings showed soil pH values to be lower in no-till (NT) systems than in soils that were under CT (Rahman et al., 2008). The lower pH in NT was attributed to accumulation of organic matter in the upper few centimetres under NT soil (Rhoton, 2000) causing increases in the concentration of electrolytes and reduction in pH (Rahman et al., 2008). Busari and Salako (2013) observed in South Western Nigeria that NT soil had a significantly higher pH at the end of the first year after tillage, but that the pH became significantly lower compared with the CT soil at the end of the second year after tillage. The latter appears to be in accord with the findings of the present work (Table 1), which are consistent with the findings of Cookson et al. (2008) that showed a decrease in surface soil pH with increasing tillage disturbance.

Earlier work of Lal (1997b) also showed a significantly higher soil pH in NT plots as compared to those in tilled plots. As indicated earlier, under high temperatures and heavy rainfall, CT results in the loosening of the soil, improved soil aeration and increased soil OM biodegradation. During the OM biodegeneration, the synthesis of organic acid (Equation 1) and the mineralisation of organically bound essential elements such as N (Equation 2) and S (Equation 3) lead to proton generations:



The protons generated as shown in Equations 1 to 3 replace basic cations on the soil exchange complex, thus bringing the cations into soil solution from where they are susceptible to loss through crop uptake and leaching, leaving H⁺ and Al³⁺ on the soil exchange complex, thus rendering the soil to be acidic in its reaction.

Phosphate sorption and external phosphate requirement

The linearized Langmuir equation gave a good fit for all the soils when C/(x/m) was plotted against equilibrium P concentration C, with coefficients of determination (R²) values > 0.95 (Figures 1 to 3). Using the equations shown in Figures 1 to 3, the sorption maxima (S_{max}) and sorption affinity (b) were calculated. The soils differed considerably in their sorption characteristics, with the S_{max} ranging from 413 to 345 mg P kg⁻¹ (Table 2). Differences in the observed sorption maxima and affinity (b) due to treatment effects were statistically significant (P ≤ 0.05). The sorption affinity (b) values ranged from 0.48 to 0.72 dm³ mg⁻¹ and the b values of the soil under NT treatment were not significantly different from those of the soil under CR (Table 2).

Soil pH

The b values were the highest in soils that had been subjected to CT treatment and the trend was similar to that of the sorption maxima (S_{max}), the external phosphate requirement (EPR), and soil pH values (Table 2). The results suggest that the highest amounts of any soluble fertiliser P added to the soils would be sorbed by reactive surfaces of soils that have been subjected to CT.

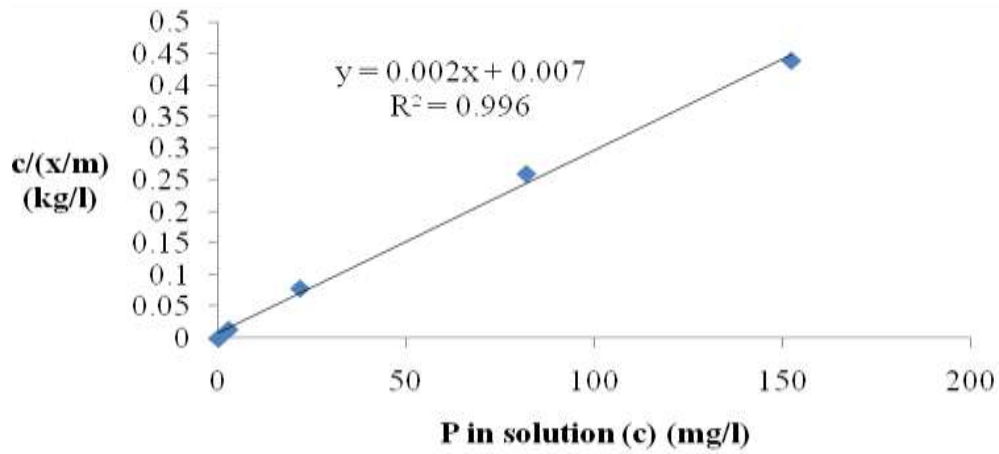


Figure 1. Crop rotation.

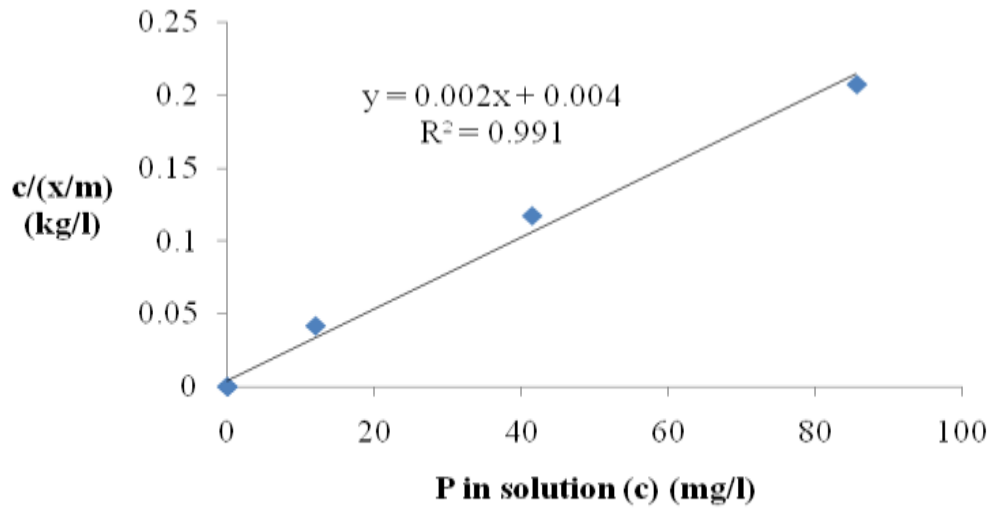


Figure 2. Conventional tillage.

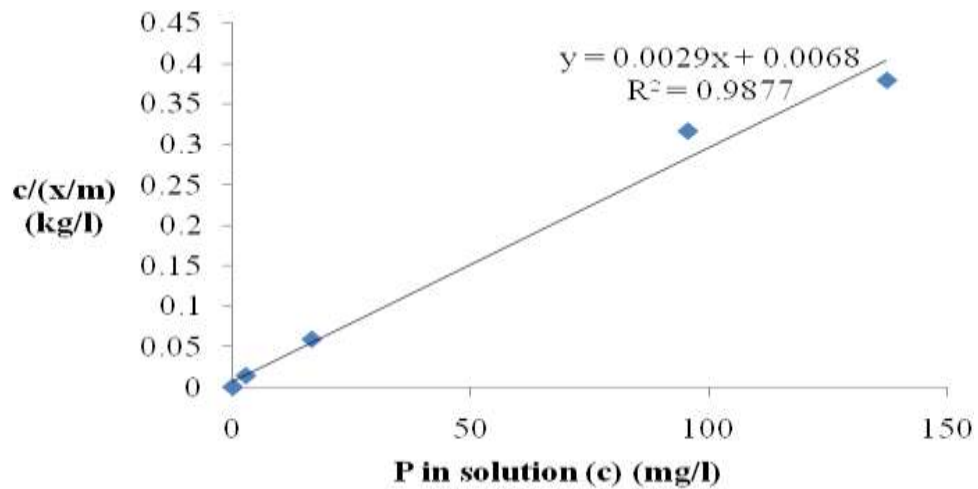


Figure 3. No-tillage.

Table 2. Means of P sorption parameters, organic matter, exchangeable aluminium and EPR ($P_{0.2}$) for crops

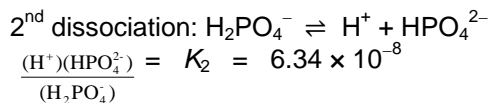
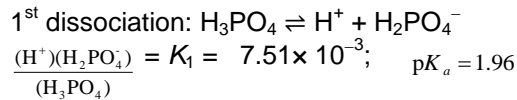
Treatment	Variables				
	OM (g kg^{-1})	Al_{exc} (cmol kg^{-1})	S_{max} (mg kg^{-1})	B ($\text{dm}^3 \text{mg}^{-1}$)	EPR ($P_{0.2}$)
CR	17.0 ^a	3.33 ^a	342.1 ^a	0.48 ^a	30.2 ^a
NT	11.2 ^a	2.55 ^a	345.4 ^a	0.48 ^a	30.0 ^a
CT	3.4 ^b	7.90 ^b	413.0 ^b	0.72 ^b	52.2 ^b
Grand mean	10.57	4.59	366.8	0.56	37.5
LSD (0.05)	4.887	1.802	22.86	0.12	8.18
CV%	28.9	24.5	3.9	11.5	13.6

Means having different letters in the same column are statistically different at 0.05 probability level. CR: Crop rotation; NT: no tillage; CT: conventional tillage.

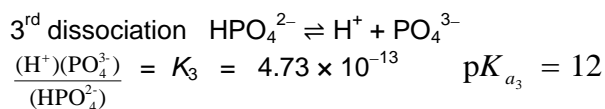
The relatively higher b, S_{max} and EPR values of the soils under CT may be attributed to the lower pH values, which is according to previous observations (Udo, 1981; Uzoho and Oti, 2005).

Plants take up P from the soil as H_2PO_4^- and HPO_4^{2-} ions and the effective concentration of these ions in solution is a function of the pH of the ambient solution.

These phosphate ions are dissociation products of the orthophosphoric acid (H_3PO_4), which is a polyprotic, weak acid. The extent to which the relative concentrations of the phosphate ions in solutions is influenced by the pH of the ambient solution is self-evident from the following sequence for the dissociation of H_3PO_4 :



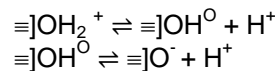
$$\text{p}K_{a_2} = 6.80$$



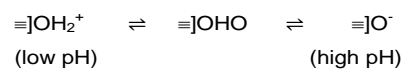
This shows that the sequence for the dissociation of H_3PO_4 yields products of diminishing acid strength and that the monovalent dihydrogen phosphate (H_2PO_4^-) species is dominant in solutions having pH 4.0 to 5.5, which suggests that this is the phosphate species that was dominant in the soils used in the present study (Table 1) and that the thermodynamic concentration of the phosphate ions in such an acid Oxisol would be governed by cations such as Fe^{3+} , $\text{Fe}(\text{OH})^{2+}$, $\text{Fe}(\text{OH})_2^+$, Al^{3+} , $\text{Al}(\text{OH})^{2+}$ and $\text{Al}(\text{OH})_2^+$ that co-precipitate with phosphate ions. Besides precipitation and dissolution of P minerals and by the sorption and desorption of inorganic P. The data given in Table 1 show that the soil

under CT whose pH was the lowest had the highest P sorption maxima and P sorption affinity values, which is consistent with earlier findings which show that in highly weathered soils like the Oxisols used in the present study, P sorption increased with decreasing pH (Udo, 1981; Uzoho and Oti, 2005) and decreases with increasing soil pH (Naidu et al., 1990).

The increase in P sorption and EPR with decreasing soil pH and the decrease in P sorption and EPR with increasing soil pH may be attributed to the amphoteric behaviour of soil colloids in such soils. The Oxisols usually contain hydrous metal oxides which like organic materials, have ionisable functional groups at their surfaces. Surface charge can develop as a result of the dissociation of these functional groups. Proton exchange reactions for surface functional groups of metal oxide minerals may be illustrated as follows:



where $\equiv\text{OH}^0$ is a surface-binding site and $\equiv\text{OH}_2^+$ and $\equiv\text{O}^-$ are proton-exchange surface complexes. The charge at the surface is a function of the pH of the surrounding water. Neutral or alkaline pH conditions generally will result in a net negatively charged surface while under acidic conditions, excess protons generally are retained at the surface yielding a net positively charged surface as follows:



It is the net increase in positive charge on the surfaces with decreasing soil pH that results in the increase in P sorption, while the decrease in P sorption with increasing soil pH may be attributed to the colloidal surfaces becoming increasingly negative charge with increasing soil pH, resulting in greater coulombic (electrostatic) repulsion and decreased P sorption (Bowden et al., 1980; Haynes, 1982). The increase in the reactive colloidal surfaces with decreasing soil pH will require more P to

Table 3. Regression of sorption maxima with exchangeable aluminium, OM and soil pH.

Variable (x)	Functions best fitting data	R ²
Exchangeable aluminium	$Y = 307.66 + 12.88 Al_{ex}$	87.6
Organic matter	$Y = 417.9 - 46.15 OM$	68.8
pH (water)	$Y = 914 - 112.3 pH$	50.8

satisfy the colloidal surface and this may explain the observed EPR values observed in soils that had been subjected to CT.

Soil organic matter

Besides electrostatic repulsion between the increasingly negative surface charge with increasing soil pH as a factor contributing to the observed decrease in P affinity, P sorption and external P requirement, the implication of soil organic matter contents in P sorption and external P requirement cannot be ruled out. As a consequence of the non-export of crop residues from the land under CR and NT, the soils under these treatments had high organic matter contents (Table 1). The P sorption affinity, P adsorption maxima and EPR values were much lower in these soils than in the soils under CT. The low biodegradation of these high contents of organic matter may have, as some of its products, humic substances such as organic acid anions such as citrate and tartarate whose concentrations in the rhizosphere may reach a level high enough to enable them compete strongly with phosphate anions for adsorption sites on reactive surfaces of solid constituents such as oxides of Fe and Al (Holford and Mattingly, 1975). Polyanionic organic complexants can also complex reactive surfaces of solid constituents such as oxides of Fe and Al.

The concentrations of organic acids in the soil solution are usually low (10^{-3} to 4×10^{-4} mol dm⁻³), but greater amounts are found in the rhizosphere of crop plants (Vance et al., 1996). It has been observed that the organic acids (the tri-carboxylic and di-carboxylic acids) that most commonly occur in soils are effective in reducing phosphate sorption, whereas monocarboxylic acids have little effect on phosphate sorption (Hingston et al., 1971; Earl et al., 1979; Yuan, 1980; Sibanda and Young, 1986; Violante et al., 1991, 1996). These properties of organic acids that occur in soils may explain the observed lower S_{max} values.

Exchangeable aluminium

The data given in Table 1 show that exchangeable aluminium (Al_{ex}) contents in the soil subjected to CR and NT were less than half of the Al_{ex} contents of the soil that was under CT. The sorption maxima increased linearly

with increasing exchangeable Al contents which accounted for about 88% of the total variations in sorption maxima (Table 3). These findings are consistent with previous observations (Udo, 1981; Bubba et al., 2003).

The significance of the inclusion of the soil variables organic matter (OM) and pH in equation after sorption maxima was regressed on exchangeable Al (Al_{ex}):

$$Y = 307.66 + 12.88 Al_{ex} \quad (R^2 = 87.6) \quad (4)$$

was tested and the following linear regression equation was obtained:

$$S_{max} = 609.0 + 5.76 Al_{ex} - 18.45OM - 50.6pH \quad (R^2 = 97.0) \quad (5)$$

The increase in the coefficient of determination ($\Delta R^2 = 106$) brought about by the inclusion of OM and pH in Equation 1 was statistically significant ($P \leq 0.05$), and the combined effects of Al_{ex} , OM and pH accounted for 97% of the total variation in sorption maxima. These findings are consistent with previous observations (Gichangi et al., 2008; Agbenin, 2003; Henry and Smith, 2002; Duffera and Robarge, 1999).

Conclusion

The results confirm that soil disturbance by conventional tillage (CT) leads to a decrease in soil organic matter contents, and to an increase in soil exchangeable aluminium (Al_{ex}), P sorption affinity (b), soil P adsorption maxima (S_{max}) and soil external P requirements (EPR). The decrease in soil organic matter contents on soils subjected to CT suggests that continued conventional tillage can impact adversely on soil quality. The increased contents of organic matter in soils under no-tillage confirm that not only maintenance of an improved soil health, but also reduction in emissions of CO₂ into the atmosphere can be achieved if the soil is not disturbed. The decrease in EPR of the soils under crop rotation (CR) and no-tillage (NT) treatments suggests that, of the three treatments used in the present study, P will be bioavailable more in soils that have been subjected to either CR or NT than in soils under CT. These results show that, because of their higher sorption capacity, soils under conventional tillage require more external P compared to the other two. This further suggests the need for the promotion of soil cropping under CR or NT

rather than CT for use by resource-poor smallholder farmers in order for them to get good value from their investment in the purchase of the small quantities of phosphatic fertilisers they apply for crop production.

Conflict of Interests

The authors have not declared any conflict of interests.

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