Phosphorus sorption capacity in relation to soil properties in profiles of sandy soils of the Keta sandspit in Ghana

S. K. Asomaning[1*], M. K. Abekoe[2] and G. N. N. Dowuona[2]
[1]*Department of Horticulture and Crop Production, University of Energy and Natural Resources, P. O Box 214, Sunyani, Ghana*
[2]*Department of Soil science, University of Ghana, P. O. Box LG245, Legon, Accra*
*Corresponding Author: samuel.asomaning@uenr.edu.gh

ABSTRACT

The sandy soils of Anloga in the Volta region form part of the Keta basin. The soils are infertile and of low productivity but are intensively cultivated for vegetables such as shallot (*Allium cepa*). Farmers have augmented the fertility of the soils by adding cow dung and poultry manure for the past seventy years. To study the P dynamics in the soils, three profiles were dug on cultivated (F) and two on uncultivated (U) fields to study P accumulation and sorption after decades of cultivation. The results showed that total P content was 533 mg P kg-^{1} at the depth of 50 cm and below in the F-profiles compared to 416 mg P kg-^{1} of similar depth of the uncultivated soils, suggesting some movement of P from the surface soil into the subsoil. The maximum P sorption capacity of the U soils was low (92 6 mg kg-^{1}) but higher than those of the F soils (58.8 mg P kg-^{1}). Multiple regression analyses showed that pH and Ca were the two major determinants of P sorption in the soils. The degree of P saturation (DPS) of the surface soils of the cultivated soils was higher than the average critical value of 25% DPS of an arable land but in the lower depths of the cultivated soils, the DPS decreased tremendously below the critical level of 25% which meant that these depths were not saturated well enough to enhance leaching of P to the underground waters.

Introduction

Phosphorus has been identified as a major nutrient deficient in soils of Ghana (Acquaye and Oteng, 1972). This is particularly true of sandy soils due to their low P buffering capacity. Soils on shallot farms in Anloga in the Volta region of Ghana are very sandy, infertile and are used for the cultivation of shallot, okro and other vegetables. Over the decades, the shallot farmers and other vegetable growers in Anloga have been applying poultry manure and cow dung to improve the fertility and also the water holding capacity of the soils. Both cow dung and poultry manure are applied at the rate of 1.3 kg m^{-2} (1.3 x 10^{4}kg/ha^{-1}). In addition, some inorganic fertilizers such as urea, ammonium sulphate and N-P-K are also added to augment the fertility of the soils (Awadzi et al., 2008). The continuous input of P fertilizers for maximizing agricultural production in these soils may result in accumulation of P thus promoting the potential of P entering into water bodies through P leaching or subsurface drainage and subsequently accelerating water eutrophication of the lagoon water.

The addition of manure and inorganic P fertilizers add P and N to the soil. If large amounts of P are accumulated in the soil, the soil's capacity to sorb additional P can be exhausted which may lead to an increased risk for P losses (Borling *et al*., 2001). Due to the sandy nature of the soil, it is likely to result in redistribution of P in the soil profiles and possibly the loss of P through leaching to contaminate surface and ground waters. This may have serious implications for ecosystem functioning and human welfare. Downward movement of P is greater when organic manure is added which might be a result of movement of organically held phosphate in the soil solution (Wild, 1959). It is therefore, necessary to investigate the P sorption characteristics of the sandy soil to ascertain the possibility of P leaching into the ground water.

Soil components such as clay type and content, soil pH, Fe and Al oxides, organic matter (OM), may affect P sorption-desorption processes in soil (Borling et al.2001; Burt et al. 2002). Among them, hydrous Fe and Al oxides retain P through specific adsorption and precipitation reactions (Sample et al., 1980). Aluminosilicate clays fix P through edge hydroxyls, while organic matter sorbs P via involvement of bridging cations such as Fe, Al and Ca (Wild, 1950). Early research showed that Fe and Al phosphates were prevalent in acidic soils, whereas Ca phosphates were dominant in calcareous soils (Lindsay, 1979). However, Beauchemin et al. (2003) found that Fe, Al and Ca phosphate were all present in both alkaline and acid soils. Pierzynski et al. (1990) observed that Al, rather than Ca, was the predominant cation associated with P in P-rich particles of heavily fertilized soils regardless of soil pH. According to Borggaard et al. (1990), aluminium and iron oxides are the main phosphate adsorbents in sandy soils. Close correlations have been found between a soil's capacity to adsorb phosphate and its content of aluminium and iron oxides, suggesting that these oxides are the main phosphate adsorbents in soils (Freese *et al.*, 1992; Torrent, 1997; Borggaard, 2002;). However, the soils at Anloga, with a pH in water ranging from 7.2-8.6, are alkaline and therefore, Ca^{2+} ions may likely be an important cation that adsorbs P.

The objectives of the study were to determine the P sorption capacity of the soils, and the soil properties that are the determinants of P sorption and the degree of phosphorus saturation in order to evaluate the possibility of P leaching to the groundwater table and the lagoon.

Materials and methods

Study Area

The study site is at Anloga, located in the southeastern corner of Ghana (Fig 1). Geologically, the site which forms part of the Keta Basin, is underlain by recent unconsolidated beach sands and lagoon clays, gravels and interlayers of thick limestone. The recent deposits rest on a series of continental beds of Middle Tertiary age. The rocks are unconsolidated limonitic argillaceous sands and gritty sands with persistent gravely beds. The Middle tertiary rocks have very permeable surface soil and subsoil resulting in low run-off as greater part of the rainfall

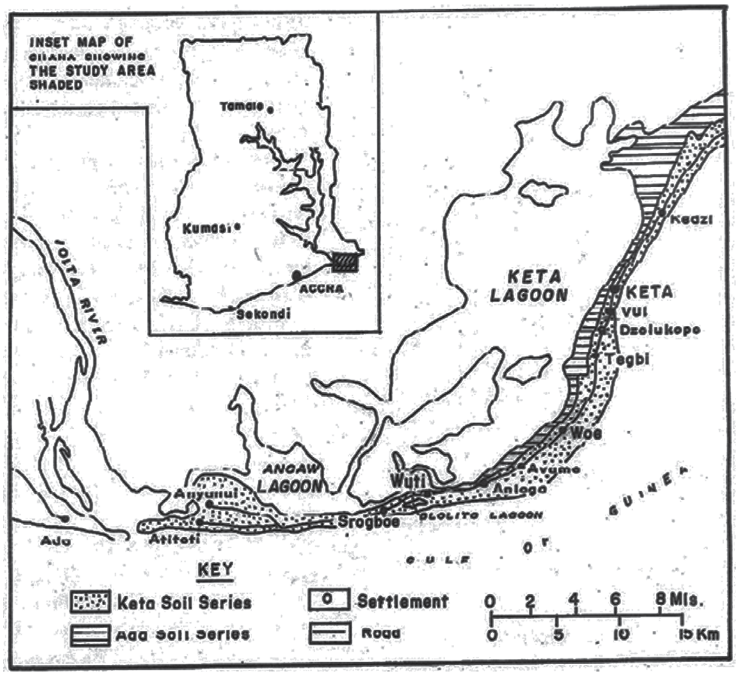


Fig .1 Map showing the project site. Adapted from Awadzi et al. (2008)

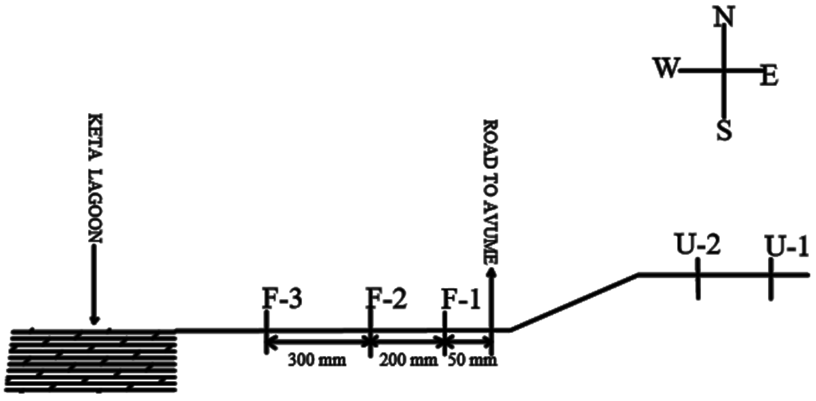


Fig 2. Location of the profiles on the topography

infiltrate into them and percolate into the ground water system. According to Walker (1962) the climate is Dry Equatorial with a mean monthly temperature of about 30 ^{0}C in the warmest month, March, and about 26 ^{0}C in the coldest month, August. This region is semi-arid with an annual rainfall of < 900 mm. Rainfall in the area is bimodal and the major season starts from April and reaches its peak in June. September to November is the minor season.

Soils and sampling

The soils used for the study belong to the Keta series, and classified as Quartzipsamment, (Soil Survey Staff, 1998.) and designated as Arenosols (FAO (1998). The soils were formed from marine sand deposits. They were sampled from both uncultivated and cultivated plots at Anloga in the Volta region of Ghana (lat. 5^o 45’ to 5^o 53’ N, long. 0^o 40’E to 1^{o}00’E) (Fig. 1).

A total of five profiles were dug along a transect. Three of the profile pits F-1, F-2 and F-3 were dug on a nearly level cultivated plain field. The two other profile pits U-1 and U-2 were dug on uncultivated field (Fig 2). Soil horizon boundaries were marked in each of the profiles and the depth of the designated horizons measured. Soil samples taken from each genetic horizon were used for laboratory analyses. The soil samples were air-dried, crushed and sieved through a 2 mm sieve to remove twigs and plant roots and stored for both physical and chemical analyses, sorption and desorption studies Poultry manure was also collected for analyses.

Soil analyses

Particle size analysis was determined by the method of Bouyoucos (1962). Soil pH was measured electrometrically in both distilled water and in 0.01M $CaCl_2$ solution at a ratio of 1:2, soil: water and 1:2, soil: 0.01M $CaCl_2$. The pH of the poultry manure was also measured in distilled water at a ratio of 1:5 manure: water. Organic carbon was determined using the wet combustion method of Walkley and Black (1934). Available phosphorus was determined using the method of Olsen et al. (1954). Total phosphorus was determined by digesting 0.5 g soil sample that has passed through a 0.180 mm sieve with 20 ml of concentrated H_2SO_4 and 1 ml of 30% H_2O_2. Phosphorus in the respective filtrates was determined using the molybdate ascorbic acid method of Watanabe and Olsen (1965). Calcium was extracted with 1 M neutral ammonium acetate (NH_4OAC, pH 7.0) and was determined using atomic absorption spectrometer. Citrate-bicarbonate-dithionite-extractable Fe and Al (Fe_d and Al_d) and oxalate-extractable Fe and Al (Fe_o and Al_o) were determined according to Mehra and Jackson (1960) and Schwertmann (1964), respectively.

Phosphorus sorption

Phosphorus sorption data were obtained using the method of Fox and Kamprath (1970). A 2.0 g soil sample was weighed accurately into each of eight 40 mL plastic centrifuge tubes. Each tube plus its content was weighed again. Twenty mL of 0.01M $CaCl_2$ solution containing 0, 2.5, 5.0, 7.5, 10, 12.5, 15.0 and 20 µg P mL^{-1} as KH_2PO_4 were added to the eight polythene tubes respectively. These quantities were equivalent to an addition of: 0, 25, 50, 75, 100, 125, 150 and 200 µg P g^{-1} of soil. In order to prevent microbial growth, two drops of toluene were added per centrifuge tube containing the suspension. The soil suspension was equilibrated by shaking end-to-end on a reciprocal shaker for thirty minutes twice a day for 7 days at room temperature (25°C) and thereafter centrifuged at 3500 rpm for 5 minutes. The supernatant was filtered through a No. 42 Whatman filter paper into a clean plastic bottle and phosphorus in the filtrate was determined using the molybdate ascorbic acid method of Watanabe and Olsen (1965). The amount of P adsorbed by the soils was calculated as the difference between the amount of P applied and the remaining P in solution. The P adsorbed by unit mass of soil (q) was plotted against P in the equilibrium solution (Ceq) using the linear form of the Langmuir equation:

$$Ceq/q = Ceq/b + 1/bk \qquad [1]$$

where q is the amount of P adsorbed per unit mass of soil (µg/g); Ceq is the equilibrium concentration of P in solution (µg/ml).

In the equation, b is the capacity factor referred to as the Langmuir P adsorption maximum, and k is a constant related to the binding energy. Conformity with the Langmuir isotherm was tested by a plot of the experimental data to the linear form of the equation. The b was determined from the slope of the plot of Ceq/q against Ceq and k calculated from the intercept. The amount of P required by the soils to attain a concentration of 0.2 mg P L-1 (standard P requirement, SPR) was calculated from the equation of the graph of P adsorbed against equilibrium P concentration (Ceq). The degree of P saturation (DPS) was obtained using the following equation:

$$DPS = (\text{Olsen extractable P/P sorption capacity}) \times 100 \qquad [2]$$

(Pautley and Sims, 2000)

Phosphorus desorption studies

Desorption studies were carried out using the residual soil which received 20 µg P ml^{-1} (i.e. 200 µg P g^{-1}). After filtering the supernatant from the previous sorption experiment, the tube plus the wet soil was weighed and a total of 20 mL of 0.01 M $CaCl_2$ solution was added to the soil in the polythene tube on a weighing balance. The suspension was shaken for two hours and centrifuged at 3500 rpm for 10 minutes at room temperature. The suspernatant was filtered through a No. 42 Whatman filter paper into a clean plastic bottle and a suitable aliquot taken for P analysis. The P carried over between desorption steps was determined from the weight of the entrapped solution that remained after decanting the supernatant solution. The extraction was repeated for three successive times and P released into the supernatant at each extraction period was then measured. The P release pattern was obtained by plotting semi-logarithm of P desorbed against equilibrium P concentration (Ceq).

Results and discussion

Soil characteristics

Some selected physical and chemical properties of the soils are shown in Table 1. The particle size analysis indicated that the two profiles U-1 and U-2 which were located on the uncultivated plot were dominated by

TABLE 1:
Some selected physical and chemical properties of the various profiles

H	Depth (cm)	C S	FS %	Silt	Clay	pH_w	pH_s	Ca^{2+} $cmol_c kg^{-1}$	TP (mg/kg)	OC (g/kg)
							Uncultivated profiles			
	U-1									
Ap	0-18	87	9	1	3	7.2	6.7	0.50	692	2.8
C1	18-49	87	9	1	3	7.8	6.0	0.19	645	2.4
C2	49-103	87	9	1	3	7.6	5.7	0.19	474	1.3
	U-2									
Ap	0-24	89	7	1	3	6.8	5.9	0.49	623	2.3
C1	24-57	89	7	1	3	7.5	6.1	0.52	415	1.1
C2	57-95	89	7	1	3	7.2	6.3	0.12	364	1.1
							Cultivated Profiles			
	F-1									
Ap	0-21	65	31	1	3	7.6	7.3	2.60	2998	5.9
Cg1	21-32	63	33	1	3	8.1	7.5	1.60	1550	2.5
Cg2	32-45	51	44	1	4	8.1	7.6	0.84	723	1.2
Cg3	45-61	44	52	1	3	8.1	7.8	0.57	526	0.9
Cg4	61-75	48	48	1	3	8.1	7.5	0.80	450	0.8
	F-2									
Ap	0-30	74	21	1	4	7.7	7.2	2.93	2768	5.7
Cg1	18-38	67	29	1	3	8.5	7.8	2.88	1396	2.6
Cg2	38-50	55	41	1	3	8.3	7.6	2.35	669	2.3
Cg3	50+	38	56	2	4	8.3	7.7	3.16	516	4.3
	F-3									
Ap	0-30	53	40	2	5	7.7	7.1	2.69	2126	4.5
Cg1	30-57	50	46	1	3	8.7	7.9	3.12	893	1.1
Cg2	57-68	29	59	4	8	9.1	8.0	2.98	541	2.8

C S =Coarse sand: 2.0 - 0.25 mm (2000 - 250 um); FS = Fine sand: 0.25 - 0.045 mm (250 - 45 um). S = Silt 0.05 – 0.002 mm (50 – 2.0 um); Clay = < 0.002 mm (2.0 um) pHw = pH in 1:2, soil :water; pHs = pH in 1:2, soil: 0.01M CaCl2 solution

TABLE 2:
Some selected properties of the manure used by the famers in the Keta Basin.

Manure type	pH	Organic carbon	Total N	Total P	Total Ca	Total Mg
		------------------------	------------------------ %	------------------------	------------------------	------------------------
Poultry manure	8.3	28.7	1.4	4.6	2.2	0.3
Cowdung	-	38.5	0.6	0.7	0.4	0.2

coarse sand which did not vary much within the profiles. The coarse sand content ranged from 87–89% of the total soil mineral fractions. The amount of fine sand varied from 7 to 9% of the total soil mineral particles. Though silt and clay contents remained uniform throughout the two profiles the amount of clay was slightly higher than that of silt. The proportion of coarse sand in the three cultivated profiles ranged from 29 to 74 % and decreased with depth whiles the proportion of fine sand generally increased with depth. The texture of the soils is sand.

The soils were near neutral to alkaline in reaction. The pH values of the uncultivated profiles ranged from 6.8 and 7.5 in water, whiles that of the cultivated profiles ranged from 7.7 to 9.1.

The high pH of the cultivated soils may be attributed to the influence of the sea spray which contains base cations and partly due to the presence of fragments of shells of aquatic organisms in the soil. The weathering of the carbonate minerals enriches the soil with the calcium. The relatively higher pH of the cultivated soils may also be attributed to the use of the groundwater which is high in soluble bases in irrigating the crops and partly to the input of the poultry manure. The poultry manure used by the farmers in the Keta basin is alkaline in nature (Table 2). Adding manure can cause an increase in soil pH due to input of large amounts of Ca and the buffering effects of added bicarbonate (Eghball, 2002). Similarly, the high exchangeable Ca of the cultivated soil profiles which were intensively manured may have been caused by the application of the poultry manure and the cow dung (Table 2). The exchangeable Ca ranged from 0.12 to 0.5 cmolc kg^{-1} for the U soils and that of the F soils ranging from 0.57 to 3.16 cmolc kg^{-1}.

Levels of organic carbon in the U soils were low and ranged from 1.1 to 2.8 g kg^{-1} as compared to 0.8 to 5.9 g kg^{-1} of the F profiles on the cultivated fields. The sandy soils were low in organic matter in conformity with similar soils described by Ahn (1970). Most soils in Ghana are inherently low in organic carbon (< 20 to 30 g kg^{-1}), probably due to the rapid turnover rates of organic materials as a result of high temperature and activities of microfauna, particularly termite (Bationo *et al.*, 2003). However, the application of the manure seems to have raised the levels of organic carbon in the cultivated soils. The organic carbon value of the soils was consistent with the findings of Awadzi et al. (2008).

The long-term addition of cow dung and poultry manure to the cultivated plots increased the total P content of the surface soils nearly 5 times over that of the uncultivated soils (Asomaning et al. 2015). The amount of total P in the soils ranged from 364 to 692 mg kg-1 for the uncultivated profiles but varied markedly within the cultivated soils and ranged from 404 to 2998 mg kg^{-1}. (Table 1) Total P distribution in the profiles showed movement of phosphorus from the surface to a depth of 50 cm and below in profiles of the cultivated soils. The total P content was 668 to 723 mg kg^{-1} at a depth of 50 cm and below in the cultivated profiles compared to 415 to 645 mg P kg^{-1} within similar depth of the uncultivated soils (Table 1). Available P ranged from 0.1 to 5.08 mg kg^{-1} for the uncultivated profiles whilst soils of the cultivated profiles which had received application of manure varied from 6.5 to 64.7 mg kg^{-1}. A significant positive correlation existed between organic

TABLE 3

Simple and Multiple regression equations for estimating P sorption maximum of the soil in all the profiles (n= 18)

Soil Property	Regression models	R^2
pH	P max (mgkg^{-1}) = -4.836 pH + 112.788	0.069*
Ca	P max (mgkg^{-1}) = -5.337 Ca + 82.991	0.379*
pH and Ca	P max (mgkg^{-1}) = 3.562pH – 6.381Ca + 56.465	0.402*
Clay and OC	P max (mgkg^{-1}) = -3.359 Org. C – 0.082 Clay + 83.335	0.267ns
pH, Ca, Clay and OC	P max (mgkg^{-1}) = - 1.103pH - 4.275 Ca - 1.722 Org. C +1.451 Clay + 89.237	0.431ns

ns = non significant; * Significant at 5%

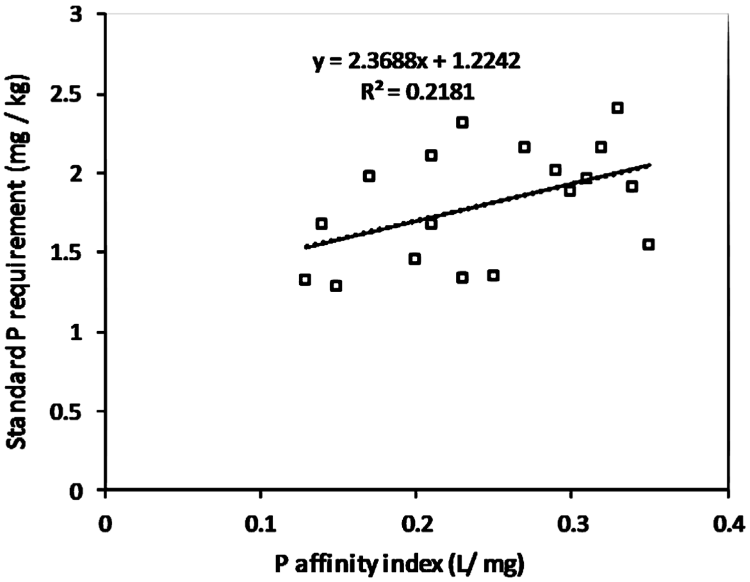


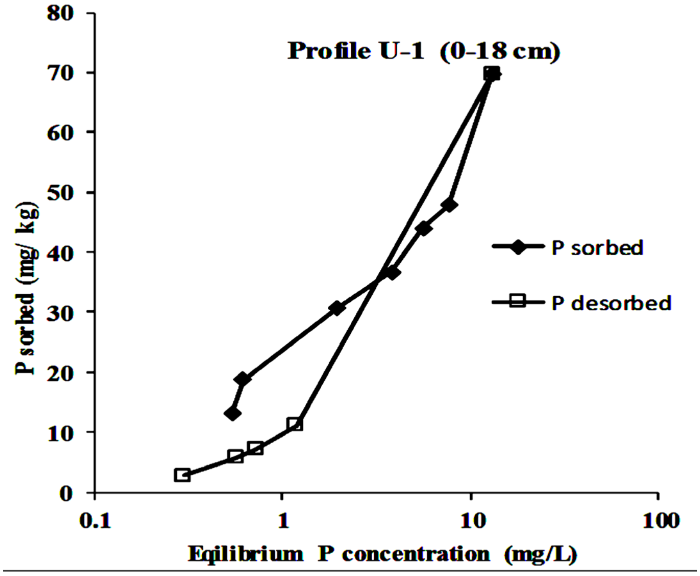
Fig. 3 Relationship between Standard Phosphorus Requirement SPR) and the Langmuir affinity index of the soils

carbon of the soils and their total P (r = 0.692*) and available P (r = 0.569*) suggesting that as the organic carbon mineralized it released P in both total and available forms. The low available P content of the soils may be attributed to their low organic matter content since organic matter has a favourable effect on P dynamics of the soil.

Phosphorus sorption in relation to soil properties

Theoretical P sorption maximum (P_{max}) calculated using the Langmuir equation and the standard P requirements are shown in Table 3. The P_{max} for the uncultivated profiles (U-1 and U-2) varied significantly within the horizons and ranged from 78.13 to 92.60 mg P kg^{-1}. Those of the cultivated profiles (F-1, F-2 and F-3) had lower P_{max} values and ranged from 58.84 to 83.30 mg P kg^{-1}. The low sorption capacity of the soils at Keta may be attributed to the low Al and Fe oxide and low clay but high sand content.

The influence of pH, organic carbon, clay and exchangeable Ca on P_{max} of the soils showed that Ca was one of the major determinants of P sorption in the soils (R^2 = 0.379*) (Table 4). Combining pH and Ca improved the



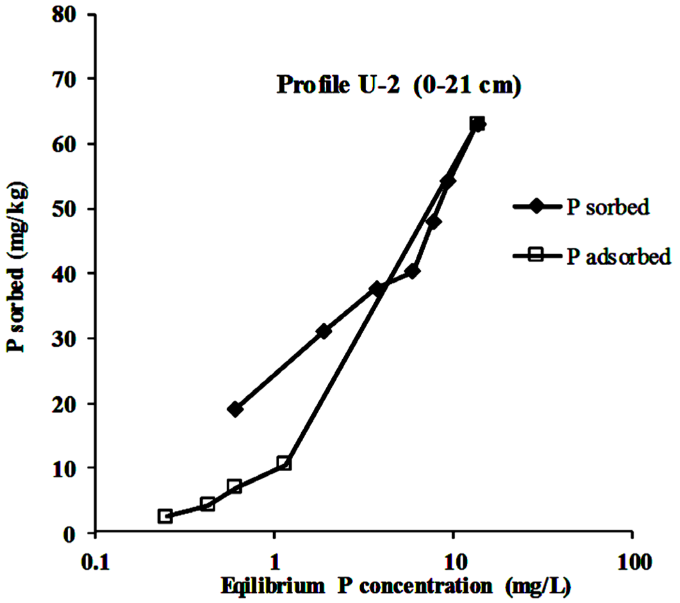
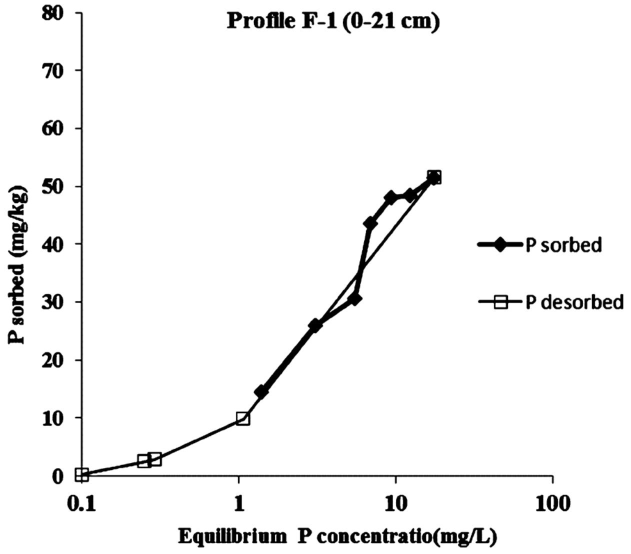
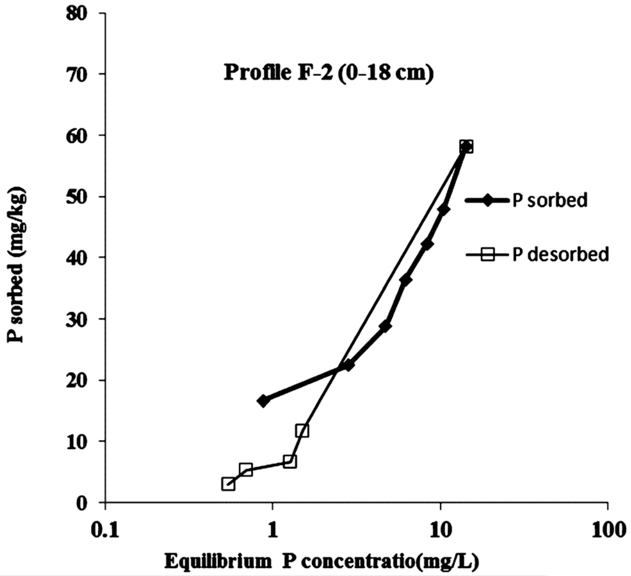


Fig 4. Phosphorus adsorption and desorption isotherms for surface horizons for the seven profiles. The four points along each desorption curve represent successive steps in the repeated extraction





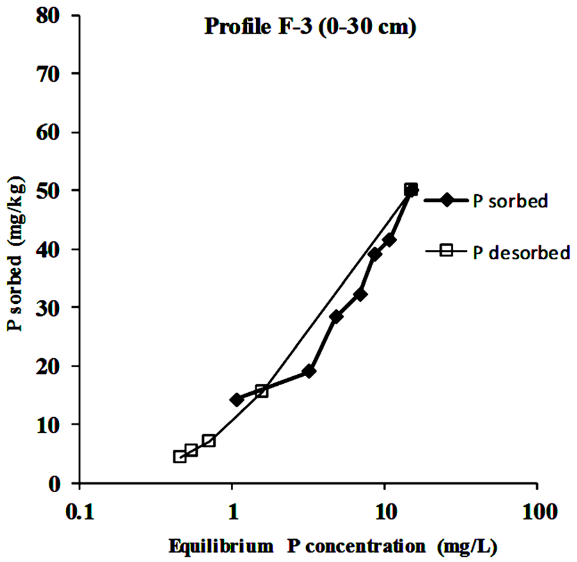


Fig. 4 (continued)

prediction of the Pmax ($R^2 = 0.402^*$). This suggests that, for these soils with high pH, Ca could be more important in adsorbing P. In alkaline soils, exchangeable Ca^{2+} and $CaCO_3$ are the main determinants of P sorption since Fe and Al activities are low in such soils.

Both Olsen-P and total P significantly but negatively correlated with Pmax (r= -0.707* and -0.722* respectively) suggesting that as P in the soil decreases P_{max} increases.

Degree of phosphorus saturation

The degree of P saturation (DPS) is a useful index for identifying fields at risk for P loading. The DPS decreased with increasing depth for all the profiles and followed the trend: F soils > U soils (Table 4). A critical DPS of 25 % has been used to determine the surplus of P that can be applied to varying soil types before the soil gets saturated with P (Sims et al., 1998). Repeated application of manure and inorganic P can cause soil total P accumulation, eventually exceeding the capacity of the soil to act as a sink. However, the results showed that in the lower depths of the cultivated soils, the DPS decreased tremendously below the critical level of 25%. This, therefore, meant that these depths were not saturated well enough to enhance leaching of P to the underground waters.

Phosphorus desorption

Figure 4 shows the patterns of P adsorption and desorption in the uncultivated and cultivated surface soils. The P adsorbed by the surface horizons of the uncultivated soils ranged from 53.6 to 63.0 mg P kg^{-1} and for F-1, F-2 and F-3 from 50.0 to 58.2 mg P kg^{-1}. (Fig. 4). The patterns of P desorption in the soils were similar. The P desorbed was initially high and was followed by gradual decreases in P release with successive extractions in all the soils (Fig. 4). Similar results for P released were observed by Dev et al. (1990) and Abekoe and Sahrawat (2001). The P released during four successive 2-h extractions with 0.01M $CaCl_2$ for these surface horizons varied from 24.54 (39 %) to 26.54 mg kg^{-1} (50 %) for profiles U-1 and U-2; 15.33 (29.8 %) to 31 mg kg^{-1} (60 %) for profiles F-1, F-2 and F-3. The surface soils of profiles U-1 and U-2 retained between 27 to 38.8 mg P kg^{-1} and those for profiles F-1, F-2 and F-3 also retaining 16 to 36.2 mg P kg^{-1} Despite the low release at the end of the four successive 2 h extractions, the solution P maintained by all the soils (0.03 – 1.59 mg P kg^{-1}) (mean of 0.81 mg P kg^{-1}) was greater than the critical level of 0.2 mg P L^{-1}. The affinity factor which expresses the bonding energy ranged from 0.14 to 0.31 $dm^3 mg^{-1}$ for the uncultivated profiles and from 0.15 to 0.35 $dm^3 mg^{-1}$ for the cultivated ones (data not shown). Thus, the bonding energy holding P molecules to the adsorption sites of these soils was low. By implication, lower energy will be required to desorb already adsorbed P ions/molecules from the adsorption site in the soils. Consequently, the release of adsorbed phosphorus for plant uptake will be fast.

The soil's capacity to resist change in the concentration of phosphorus in soil solution is called phosphorus buffering capacity. It is the capacity of soil to maintain a given P level in soil. The low bonding energy indicates that the soils have low potential P buffering capacity (PBC). As judged from its extractability in 0.01 M $CaCl_2$, these soils will continue to have enough P in solution for growth of crops.

Conclusion

Total phosphorus distribution in the profiles showed some P movement from the surface to a depth of 50 cm and below in profiles of the cultivated soils but the degree of P saturation (DPS) decreased with increasing depth for the cultivated profiles. In the lower depths of the cultivated soils, the DPS decreased below the critical level of 25% which meant that these depths were not saturated well enough to enhance leaching of P to the underground waters. Therefore, the results suggest that intensive crop production on alkaline sandy soils under tropical semi-arid conditions may be environmentally sustainable even after decades of manure application.

Acknowledment

The authors thank Ecological Laboratory, University of Ghana for the financial support. The help offered by the technical staff of the Ecological Laboratory in the course of the analytical work is very much appreciated.

References

Abekoe , M.K. and K.L. Sahrawat. (2001). Phosphate retention and extractability in soils of the humid zone in West Africa. Geoderma **102**, 175-187.

Acquaye, D.K. and J.W. Oteng (1972). Factors influencing the status of phosphorus in surface soils in Ghana. Ghana Jnl. Agric. sci. 5: 221-228.

Ahn, P. (1970). West African Soils.Oxford University Press, Ely House, London W.1.

Asomaning, S. K., Abekoe, M K., Dowuona, G. N. N., Borggaard, O. K., Kristensen, J. and Breuning-Madsen, H. (2015). Sustainable long-term intensive application of manure to sandy soils without phosphorus leaching: a case study from Ghana, Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, DOI:

Awadzi,T.W.,.Ahiabor, E. and Breuning-Madsen, H. (2008). The Soil-Land use System in a Sand Spit Area in the Semi-Arid Coastal Savanna Region of Ghana- Development, Sustainability and Threats. West African Journal of Applied Ecology. Vol. 13. 181-194.

Bationo, A., A.U. Mokwunye., P.L.G. Vlek, S. Kaola and B.I. Shapiro. (2003). Soil Fertility Management for sustainable landuse in West Africa Sudano-Sahelian Zone. In: Soil Fertility Management in Africa: A regional Perspective, Gichuru et al. (Eds) Acad. Sci. Pub. (ASP) and TSBF-CIAT, Nairobi, Kenya.

Beauchemin S, Hesterberg D, Chou J, Simard R.R, Sayers D.E (2003). Speciation of phosphorus in phosphorus-enriched agricultural soils using X-ray absorption near edge structure spectroscopy and chemical fractionation. Jounrnal of Environmental Quality. **32**, 1809-1819.

Borggaard O.K. (2002). Soil Chemistry in a Pedological context. 6th Edition, DSR Forlag, Frederiksberg, Denmark (6th ed.).

Borggaard. O. K. and Moberg P.M. (1990). Estimation of critical phosphate loads in Danish sandy soils. In: Soil Vulnerability to pollution in Europe. N.H Batjes and E . M. Bridges (eds.) ISRIC, Waggeningen, The Netherlands, pp. 71 -75.

Borling, K, Otabbong E, Barberis E (2001). Phosphorus sorption in relation to soil properties in some cultivated Swedish soils. Nutrient Cycling in Agroecosystem **59**, 39-46. 10. 1023/A:1009888707349

Bouyoucos, G.J., 1962. Hydrometer method improved for making particle size anlyses of soils. Agron. J. **54**, 464-465.

Burt R, Mays M.D, Benham E.C, Wilson M.A (2002). Phosphorus characterization and correlation with properties of selected benchmark soils of the United States. Communications in Soil Science and Plant Analysis **33**, 117-141. Doi: 10.1081/CSS-120002382

Dickson, K.B, and Benneh G. 1995. A new geography of Ghana. 3rd ed. Essex: Longman.

Dev, G., S.N. Sagger, and A.C. Vig. (1990). Effect of extended rice-wheat sequence on available phosphorus status in soils. In Stewart, J.W.B. (ed), Soil Quality in Semi-arid Agriculture. Pp. 108-115.

Eghball, B. (2002). Soil properties as influenced by phosphorus and nitrogen-based manure and compost applications. Agron. J. **94**: 128-135.

FAO, (1998). World References Base for Soils Resources. World Soil Research Report 84. FAO, Rome. Freese, D., S.E.A.T.M. van der Zee and W.H. van Riemsdijk 1992. Comparison of different models for phosphate sorption as a function of the iron and aluminium oxides of soils. J.Soil Sci. **43**: 729 – 738.

Freese, D., S.E.A.T.M. van der Zee and W.H. van Riemsdijk (1992). Comparison of different models for phosphate sorption as a function of the iron and aluminium oxides of soils. J.Soil Sci. **43**: 729 – 738.

Fox, R.L. and E.J. Kamprath, (1970). Phosphate sorption isotherms for evaluating the phosphate requirements of soils. Soil Sci. Soc. Am. Proc. **34**: 902–907.

Juo, A.S. R., and R.L Fox (1977). Phosphate sorption charateristics of some benchmark soils of West Africa. Soil Science. **114**: 370 – 376.

Kleinman P.J.A., Bryant R.B. and Reid W.S. (1999). Development of pedotransfer functions to quantify phosphorus saturation of agricultural soils. J. Environ. Qual. **28**: 2026-2030.

Mehra, O. P. and Jackson M. L. (1960). Iron oxide removal from soils and clays by a ditionite-citrate system buffered with sodium bicarbonate. Clays and Clay Minerals **7**:317-327.

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. USDA circ. 939. Washington D.C.

Osodeke, V.E., D. O.K. Asawalam, O.J. Kamalu, and I.K. Ugwa. (1993). Phosphorus sorption characteristics of some soils of the rubber belt of Nigeria. Commun. Soil Sci. Plant Anal. **24** : 1733 -1743

Pautley M.C and J.T Sims (2000). Relationships between soil test phosphorus, soluble phosphorus saturation in Delaware soil. Soil Sci Soc Am J . **64**: 765 - 773

Pierzynski, G.M, Logan, T.J, Traina, S.J. and Bigham, J.M (1990). Phosphorus chemistry and mineralogy in excessively fertilized soils: Quantitative analysis of phosphorus-rich particles. Soil Science Society of American Journal **54**, 1576-1583.

Sample, E. C., Soper, R. J. and Racz, G. J. (1980). Reactions of phosphorus fertilizer in soils. In: F. E. Khasawneh, E. C. Sample and E. J. Kamprah (eds.) The role of phos[horus in Agriculture. Pages 263-310. ASA., CSSA, SSSA. Madison, W.I., U.S.A.

Schwertmann, U. (1964). Differenzierung der Eisenoxide des bodens Durch extraction mit Ammoniumoxalat-Lösung. Z PflanzenernährDüng Bodenk. **105**:194–202.

Sims, J.T., Simard, R .R. and. Joern, B.C. (1998). Phosphorus loss in Agricultural drainage: Historical Perspective and current Research. J. Environ. Qual. **27**: 277 – 293.

Soil Survey Staff. (1998). Keys to Soil Taxonomy, 8th edn. USDA-NRCS, Washington,

Torrent J. (1997). Intereactions between phosphate and iron oxide. In: Soil and Environment – Soil Processses from Mineral to Landscape Scale. K. Auerswald, H.

Walkley, A. and Black, I. A. (1934). An examination of the dehtjareff method for determining soils organic matter, and a proposed modification of the chromic acid titration method. Soil Science. **37**: 29-38.

Watanabe, F.S and S.R. Olsen, (1965). Test of an ascorbic method for determining phosphorus in water and NaHCO3 extracts from soil. Soil Sci. Am. Proc. **29**: 677-678.

Wild, A. (1950). The retention of phosphate by soils: A review. European Journal of Soil Science **1**, 221-238.