Phosphorus status of some semi-arid agricultural soils of northern Ghana

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SUMMARY

The phosphorus status of selected soils of the semi-arid savanna zone of northern Ghana was studied by determining their available organic and total P content and the P sorption characteristics. The available P varied from 1.7 to 8.7 mg kg^{-1}, total P from 116 to 215 mg kg^{-1} and organic P from 63-125 mg kg^{-1}. The organic P formed about 61 per cent of the total P and the C:P ratio was mainly below 150. The capacity to sorb P varied among the soils, but in general the soil developed over basic parent material (greenstone), sorbed more phosphorus than those over acidic rock (granite). The P sorption maximum values correlated significantly with organic carbon ($r = 0.964^*$) and free iron extractable with dithionite-citrate ($r = 0.958^*$) but not with *p*H, CEC and clay. Thus, free iron oxide and organic carbon in the soils were the main factors responsible for P sorption, accounting for 97 per cent of the observed variation. It is recommended that the use of organic residues and manure and application of inorganic fertilizers to supply about 30-35 kg P ha^{-1} would improve P availability in these soils.

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RÉSUMÉ

OWUSU-BENNOAH, E., AMPOFO, J.G. & ACQUAYE, D. K.: *Le statut phosphore dans quelques sols agricoles semi-arides au nord du Ghana.* Le statut phosphore de sols sélectionnés de la zone savane semi-aride au nord du Ghana était étudié par la détermination de leur disponible contenu organique et P total ainsi que les caractéristiques sorption de P. Le P disponible variait de 1.7 à 8.7 mg kg^{-1}, P total de 116 à 215 mg kg^{-1} et P organique de 63-125 mg kg^{-1}. Le P organique constituait environ 61 pour cent du P total et la proportion C:P était principalement au-dessus de 150. La capacité de sorber P variant parmi les sols, mais en général le sol dérivé de matiére parentale fondamentale (pierre verte) sorbait plus de phosphore que ceux de roche acide (granit). Les valeurs maximum de sorption de P avaient corrélées considérablement avec carbon organique ($r = 0.964$) et le fer libre extractible avec dithionite-citrate ($r = 0.958$) mais pas avec *p*H, CEC et argile. Donc, oxyde de fer libre et carbone organique dans les sols étaient les facteùrs majeures responsables de sorption de P, représentant 97 pour cent de la variation observée. Il est conseillé que l' utilisation de résidus organiques, le fumier et l'application d'engrais inorganiques pour fournir environ 30-35 kg P ha^{-1} pourrait améliorer la disponibilitié de P dans ces sols.

Introduction

The soils of northern Ghana fall within the semi-arid zone with pronounced dry season (4-5 months) and up to 1300 mm annual precipitation. The region is an important agricultural area where a wide range of crops including maize, sorghum, yam, groundnut, pigeon pea, cowpea and soyabean are produced. Preserved and utilized trees are mainly shea butter (*Butyrospermum parkii*) and locus bean (*Parkia biglabosa*). Due to the topography of the area which makes it suitable for mechanized farming, efforts are being made to develop productive and efficient cropping systems in the region to produce enough food to meet the food security for a population that is growing at a rate of more than 3 per cent per annum.

Generally, the soils of the region are characterized by sandy to sandy loam textures, low clay and low organic matter contents resulting in low cation exchange capacity. Phosphorus deficiency is widespread and is a major constraint to crop production in the zone (Halm, 1968; Konabo, Halm & Obeng, 1978; Owusu-Bennoah & Acquaye, 1989). In some soils, the deficiency is so acute that plant growth ceases as soon as the P stored in the seed is exhausted. The problems associated with P deficiency and P sorption on these soils have been attributed mainly to large portions of Al and Fe oxides and hydroxides which sorb labile or fertilizer P from the soil solution (Tiessen 1990). Phosphorus status of some ironpan soils in the regon have been well documented. (Kanabo, Halm & Obeng, 1978; Owusu-Bennoah & Acquaye, 1989; Tiessen *et al.*, 1991), but there is dearth of information on these important soils. Studies concerned with the evaluation of P status and P sorption of these agriculturally important soils are of tremendous interest, especially if the results can be related to fertilizer requirements.

The present study was undertaken to assess the P status of four representative soils from the semi-arid zone of Ghana in relation to their properties.

Materials and methods

Soils

The soils used for this study were Kupela, Mimi, Nangodi and Tingoli series. The general properties and geographical distribution of the soils have been described by Adu (1969). Under USDA Soil Taxonomy (Soil Survey Staff, 1975), the soils are classified as Tropoaqualf, Rhodustalf Ustropept and Paleustalf in that order (Table 1). Apart from the Tingoli soil series which was sampled from a cultivated field planted to sorghum, the rest of the soils were sampled from uncultivated fields.

TABLE 1

Taxonomy and Parent material of the Soils

Soil series	*Soil classification USDA (Soil Taxonomy)*	*Parent material*	*Distribution*
Kupela	Tropoaqualf	Granite	Alluvium soil
Mimi	Rhodustalf	Sandstone	Piedmont drift alluvium
Tingoli	Paleustalf	Sandstone	Summit/Upper slope
Nangodi	Ustropept	Greenstone	Middle slope

All soil samples were taken at the depth of 0 - 20 cm, air-dried and gently crushed to pass through a 2 mm sieve. The fine earth fraction was stored and used for laboratory analysis.

Laboratory methods

Particle size distribution of soils was determined by the pipette method after dispersion with sodium hexametaphosphate. Soil *p*H was measured in a 1:2 soil:0.01*M* $CaCl_2$ suspension. Organic carbon was determined by the Walkley-Black method (Walkley & Black, 1934). Exchangeable bases (Ca, Mg, K and Na) were extracted with 1*M* ammonium acetate solution at *p*H 7 (Thomas, 1982). Potassium and sodium in solution were determined by flame photometry while concentrations of Ca and Mg were determined by titration with 0.02*N* EDTA (Moss, 1961). Dithionite-citrate extractable iron (Fe_d) and aluminium (Al_d) were determined by atomic absorption spectrophotometry after extraction with dithionite-citrate-bicarbonate (DCB) (Mckeague, 1978) and oxalate-extractable iron (Fe_o) by the method of Schwertmann (1973). Total N was determined by semi-micro Kjeldahl procedure (Bremner, 1965). Total P was determined by $HClO_4$-H_2SO_4 digestion and P analyzed colorimetrically (Watanabe & Olsen, 1965).

Organic P was estimated as the difference between extractable inorganic P before and after ignition (Legg & Black, 1955). Available P of the soils was determined by extraction with 0.5*M* $NaHCO_3$ (*p*H 8.5) and the P concentration measured by the molybdate blue method as described by Watanabe & Olsen (1965).

Sorption studies

Phosphorus sorption was determined by equilibrating 5 g soil with 50 ml of 0.1 *M* KCl solution containing various amounts of P (0 - 160 mg kg^{-1} P as KH_2PO_4) in a 100 ml centrifuge tube. Two drops of toluene were added to inhibit microbial growth. The suspensions were shaken on a mechanical shaker for 30 min twice daily for 6 days, centrifuged and the P in the supernatant was determined colorimetrically (Watanabe & Olsen, 1965). The difference between phosphate concentration before and after shaking with soil sample was used to calculate the quantity of phosphate sorbed by the soil sample.

Theoretical sorption maxima were calculated by fitting data obtained to the linear form of the Langmuir equation:

$$C/x/m = 1/kb + C/b$$

where C is the P concentration in the equilibrium solution, x/m is the amount of P sorbed per unit weight of soil, b is the sorption maximum and k is a constant relating to binding strength of P on the soil. A plot of C/x/m versus C, with a slope of $(b)^{-1}$ was used to calculate the sorption maxima.

Results and discussion

Characteristics of the soils

Soil texture varied from loamy sand, sandy loam to loam. The range in *p*H amongst the four soils was small, from 5.4 to 6.1, reflecting a low-leaching regime. The organic carbon contents were low, about 9-13 mg g^{-1} (mean 11 mg g^{-1}); the total N values were also low and ranged from 0.60 - 0.69 mg g^{-1}; the C:N ratios were wide (15-19.4). This is a reflection of the low organic matter contents typical of Ghana savanna soils (Tiessen *et al.*, 1993). Similarly, the CEC values were generally low (< 10cmol (+) kg^{-1}) suggesting the predominance of low activity clays and quartz sand in the soils. Table 2 shows that dithionite-citrate extracted considerably more iron from all the soils (29-209 mg g^{-1}) than did oxalate (0.7-2.4 mg g^{-1}).

The amount of Al extracted by dithionite-citrate was 0.51 - 1.9 mg g^{-1}. Nangodi and Tingoli soils had the highest values of Fe_d, Fe_o and Al_d. The results seem to indicate that most of the Fe present in these soils were more in crystalline than amorphous form.

TABLE 2

Some Physical and Chemical Properties of the Soils

Soil series	pH in 0.01 M $CaCl_2$	Particle size distribution (per cent)			Org. C	Tot. N	C/N (mg g^{-1})	Exchangeable Bases (cmol$_c$ kg^{-1})				CEC	Fe_o	Fe_d	Al_d (mg g^{-1})
		Clay	Silt	Sand				Ca	Mg	K	Na				
Kupela	6.1	20	38	42	11	0.63	17.5	4.8	3.0	0.51	1.17	9.6	1.1	44	0.51
Mimi	5.5	8	14	78	9	0.60	15.0	3.0	0.8	0.34	0.17	4.8	0.7	29	0.57
Tingoli	5.8	10	30	60	12	0.69	17.4	2.8	1.0	0.44	0.17	5.4	2.0	63	0.97
Nangodi	5.4	14	20	66	13	0.67	19.4	5.8	2.2	0.28	0.22	8.6	2.4	109	1.9
Mean	5.7	13	25.5	61.5	11.3	0.65	17.3	4.1	1.75	0.39	0.43	7.1	1.55	61.25	0.99

Clay < 0.002 mm; Silt (0.2 - 0.002 mm); Sand (2 - 0.2 mm).

The P status of the soils is shown in Table 3. The total contents of the soils ranged from 116 to 215 mg kg^{-1} (mean 155 mg kg^{-1}). Values reported for some surface soils from the West African savanna fall within the range of 13 to 630 mg kg^{-1} P (Jones & Wild, 1975). Because total P is an inherent property of soils, the generally low total P values in these soils could be related to the nature of the parent material. Thus, Kupela, Mimi and Tingoli series developed which over acidic parent materials had lower total P contents (mean value 135 mg kg^{-1}) than Nangodi series which developed over basic rocks (215 mg kg^{-1}) (Table 3). Similar results have been reported for other savanna soils (Enwezor & Moore, 1966; Acquaye & Oteng, 1972; Ayodele & Agboola, 1983). Organic P content varied from 63 to 125 mg kg^{-1} (mean 95 mg kg^{-1}). The mean organic P accounted for 61 per cent of the total P contents. The results agree with other previous findings (e.g. Acquaye & Oteng, 1972; Udo & Dambo, 1979; Ayodele & Agboola, 1983). The low organic P contents might be due to the low vegetative cover

TABLE 3

Phosphorus Status of the Soils

Soil series	*Total P* (mg kg^{-1})	*Org. P* (mg kg^{-1})	*Org. P as per cent of total P*	*Available P (mg kg^{-1})*	*C:P*	*Sorption max* b_1* (mg kg^{-1})	*b_2* (mg kg^{-1})	*total* (mg kg^{-1})	*Standard P conc. at 0.2μg ml^{-1}** (mg kg-^{1})*
Kupela	116	73	62.9	1.7	151	167	333	500	33
Mimi	118	63	53.4	5.7	143	107	193	300	12
Tingoli	171	125	73.1	3.7	96	175	417	592	22
Nangodi	215	120	55.8	8.7	108	240	546	786	31
Mean	155	95	61	5.0	125	172	372	544	24

*b_1 = Sorption maximum extrapolated from the first linear portion of the sorption isotherm (Fig. 2)
b_2 = Sorption maximum extrapolated from the second linear portion of the sorption isotherm (Fig. 2)
** Standard P conc. at 0.2 μg ml-^{1} is the amount of fertilizer P required to attain equilibruim soln P conc. of 0.2 μg ml-^{1}

which had consequently resulted in low organic matter contents. The organic C: organic P ratios were relatively low (with a mean of 150). Mineralization of organic P resulting in increased available P will be expected in these soils (Tisdale *et al.*, 1990). Olsen extractant is widely used in Ghana as an indicator of available P in soils with *p*H 5.5 - 7.0. Available P ranged from 1.7 to 5.7 mg kg^{-1} in Kupela, Mimi and Tingoli soils while Nagodi had almost 9 mg kg^{-1}. None of these soils had a recent history of P fertilization, so the available P parameter represents a background level for agricultural soils in this zone. Acquaye & Oteng (1972) reported that most soils containing extractable P of less than 10 mg kg^{-1} as determined by Olsen method, were low in available P. Based on this information, the soils could be considered to be low in fertility with respect to P compared to forest soils in Ghana (Owusu-Bennoah & Acquaye, 1989) thus confirming P availability as a limiting factor in crop production in semi-arid zones of Ghana (Tiessen *et al.*, 1991).

P sorption

Fig. 1 presents the P sorption isotherms for the four soils. They indicate different sorption characteristics: Mime series sorbed the lowest amount of P while Tingoli series sorbed the highest at any equilibrium P concentration. The theoretical sorption maxima (b_1) based on the first linear portion of the graph (Fig. 2) and estimated by the Langmuir equation ranged from 107 - 240 mg kg^{-1} (mean 172 mg kg^{-1}) (Table 3) and the corresponding b_2 values ranged from 193 to 546 mg kg^{-1} (mean 372 mg kg^{-1}). With the exception of Nangodi series, the soils can be considered to have relatively low P sorption capacities. The low capacities could be due to the fact that the iron oxides were more in the crystalline than in the amorphous form. This agrees with data

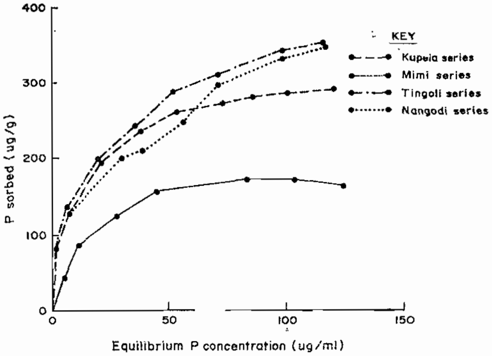

Fig. 1 P sorption isotherms for the four soils

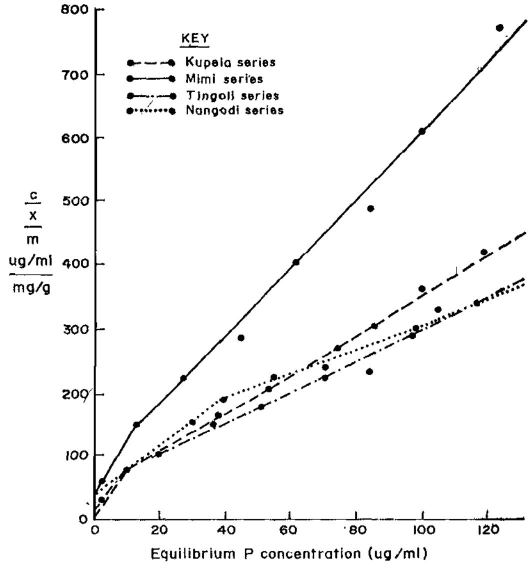

Fig. 2. Langmuir isotherms for the four soils

reported by Enwezor & Moore (1966) and Juo & Maduakor (1974) for some Nigerian savanna soils and Owusu-Bennoah & Acquaye (1989) for some soils from Ghana. The coarse-texture upland soils (formed from granite or sandstone) with low P sorption capacities occupy a large area of the arable land in the semi-arid savanna zone of Ghana, whereas the high P sorption soil, Nangodi, derived from basic rocks (greenstone) occupy extremely small scattered areas in the zone.

Correlation and regression analyses showed the P sorption maxima (b_1 values) as dependent variable (Table 4) were positively correlated with organic carbon (r = 0964*) and free iron oxide extractable with dithionite-citrate (r = 0958*). A similar relationship between b_1 and organic carbon has been reported for Malaysian soils (Ahmed & Foster, 1983) and for some Ghanaian soils (Kanabo, Halm & Obeng, 1978). On the other hand, Ayodele & Agboola (1983), working on savanna soils in western Nigeria, found no correlation between sorption maximum and organic carbon. Although organic carbon is significantly related to sorption maximum, it is unlikely that P combines directly with organic constituents but with the associated cations particularly iron and aluminium (Williams, Scott & MacDonald, 1958; Lopez-Hernandez & Burham, 1974).

Sorption maxima were significantly correlated with dithionite-citrate extractable free iron oxides, but there was no significant correlation of P sorption with oxalate extractable iron oxides (Table 4). These results are similar to previous findings by Lopez-Hernandez & Burham (1974), Owusu-Bennoah & Acquaye (1989), and Arduino *et al.* (1993).

Correlation between sorption maxima (b_1 values) and free Al_2O_3 was not significant. Ahenkorah (1968) also found no significant correlation between P sorption maximum and free Al_2O_3 on some Ghanaian cocoa-growing forest soils. This suggests that the role of free Fe_2O_3 in P sorption in these soils is more important than that of Al_2O_3. This could be because of the relatively higher amounts of iron oxides present in comparison with the amounts of free aluminium oxides. Owusu-Bennoah & Acquaye (1989) also explained that the relative importance of iron and aluminium oxides

TABLE 4

Coefficient of Determination (r^2) between Sorption Maximum (b_1) and some Soil Properties and the Linear Regression Equation

Soil property	*Coefficient of determination*	*Linear regression equation*
Organic carbon	0.929*	y = -173.29 + 30.71 (Org. C)
Free Fe_2O_3 (dithionite-citrate)	0.918*	y = 80.31 + 1.50 (Fe_d)
Free Fe_2O_3 (oxalate)	0.828NS	y = 74.52 + 63.05 (Fe_o)
Free Al_2O_3 (dithionite-citrate)	0.763NS	y = 99.09 + 74.09 (Al_d)
CEC	0.369NS	y = 72.69 + 14.02 (CEC)
Clay (per cent)	0.163NS	y = 118.24 - 4.15 (% Clay)
*p*H	0.031NS	y = 345.15 - 30.33 (*p*H)

* denotes significance at P = 0.05; NS = not significant

in P sorption depends on soil *p*H, the former being more important under more acid conditions.

Other soil properties such as *p*H, CEC and clay content were not significantly correlated with P sorption. Multiple regression of sorption maximum on free iron oxides and organic carbon showed that variation in sorption maximum could be accounted for by these two variables:

Sorption maximum = -64.716 + 0.740 (Fe_d) + 17.035 (Org. C) r=0.968. Owusu-Bennoah & Acquaye (1989) also observed that free iron oxides and organic carbon are the most important soil variables which determine the sorption capacity in soils of the area. Lopez-Hernandez & Burham (1974) stated that iron oxides when intimately associated with organic matter can sorb much more phosphate than the same amount of free Fe_2O_3.

Conclusion

Sustained agricultural production on these savanna soils will require management technologies that will promote nutrient availability in general. To maintain an adequate pool of labile P in these soils will require input of external sources. The low sorption capacity of the majority of the soils (Tingoli, Mimi and Kupela) which occupy large areas will necessitate the use of low to medium levels of P fertilizers (Manu, Batiano & Geiger, 1991). P can also be supplied from organic manure sources including manure and crop residues which are abundant in the zone. On the other hand, with soils of high P sorption e.g. Nangodi, one may settle for a less soluble P source that releases P in soil solution in smaller concentrations spread over a longer period of time. This is expected to slow down the sorption reaction in the soil and maintain fertilizer P in plant-available form for a longer period.

The evidence presented in the study also supports the idea that crystalline Fe-oxides might provide most of the P sorbing surfaces of the soils. Consequently, knowing the specific surfaces of these oxides can contribute to better understanding of the P sorption behaviour of the soils.

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