

International Journal of **Soil Science**

ISSN 1816-4978



Academic
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Research Article

Phosphorus Adsorption Isotherms in Relation to Soil Characteristics of Some Selected Volcanic Affected Soils of Foubot in the West Region of Cameroon

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Abstract

This study evaluated volcanic influenced soils from the Foubot areas of Mbankouop, Paponoun, Monoun and Baigom plain for their physico-chemical soil properties and their phosphorus (P) sorption characteristics. The fact that P in soils is not readily available to plants necessitates investigation in order to determine the quantities to be added and avoid excesses which can lead to water pollution by fertilizers. The Freundlich, Langmuir, Temkin and Van Huay adsorption isotherms were used to describe P adsorption processes. The adsorption isotherms showed that rates of P adsorption increased with increased concentration of P, but at a certain level of higher concentration, the level of P became almost constant, because the soil had no more capacity to adsorb. P adsorption capacity decreased in the order Monoun>Paponoun>Mbankouop>Baigom plain with maximum adsorption values of 3020.86, 2174.04, 1949.12 and 497.90 mg kg⁻¹ soil recorded, respectively. Accuracy of fitness of data of the four samples into the adsorption equations increased in the order Langmuir, Van Huay, Temkin and Freundlich with coefficient of determination (R²) values of 0.819, 0.902, 0.967 and 0.972, respectively. The capacity of each sample to adsorb P was significantly correlated with amorphous iron content ($r = 0.949^*$), but weakly negatively correlated with the available P, exchangeable bases and silt content of the soils. Management practices involving the use of organic materials and liming as a basis for P sorption reduction will be useful for crop production in Foubot.

Key words: Phosphorus, volcanic soil, adsorption isotherms, amorphous iron, liming

Received: October 16, 2015

Accepted: December 23, 2015

Published: March 15, 2016

Citation: Njoyim Estella Buleng Tamungang, Mvondo-Zé Antoine David, Mofor Nelson Alakeh and Onana Adibime Adalbert, 2016. Phosphorus adsorption isotherms in relation to soil characteristics of some selected volcanic affected soils of foubot in the west region of Cameroon. *Int. J. Soil Sci.*, 11: 19-28.

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Soil and its contents are important factors that determine the yield of agricultural production. As with other living beings, plants need food for their growth, development and reproduction. The challenge for agriculture in the coming decades will be to meet the world's increasing demand for food in a sustainable manner. Declining soil fertility and mismanagement of plant nutrients have made this task more difficult (Yerima and van Ranst, 2005; Yaser and Rahim, 2013). Amongst the three elements (Nitrogen, N, Phosphorus, P and Potassium, K) which constitute the N-P-K fertilizer, N and K are readily made available to plants whereas P is most at times unavailable to plants. Phosphorus is an essential plant nutrient and its deficiency tends to limit plant growth (Tening *et al.*, 2013). In the tropics, phosphorus is often the most limiting plant nutrient, primarily due to the challenges encountered in the management of phosphorus (Silva and Uchida, 2000).

Phosphorus (P) is an essential component of cell membranes, plant genetic material and of energy storage and transfer systems for chemical reactions in plant cells. Early plant growth is particularly dependent on P because of the needs for rapid cell division and expansion (Silva and Uchida, 2000; Bolland *et al.*, 2001). Roots of all plant species can only take up water-soluble P from soil solution. Plant roots intercept P in moist soil as the roots grow through the soil and P moves through the soil solution to the roots by diffusion. The rate of diffusion depends on the proportion of the P in solution. The smaller the proportion, the slower it moves and so the more P is required to give an adequate rate of P supply. The proportion in solution depends on the buffering capacity of the soil for P, which is the capacity of the soil to sorb P. The P removed from soil solution by plant roots needs to be replaced and depends on the capacity of the soil to replenish the P. The P is replaced by (1) Desorption of sorbed P from nearby sources, (2) P released from soil organic matter as a result of the activity of soil organisms on the organic matter and (3) Application of fertilizer to the soil. Both the concentration of P in soil solution (intensity factor) and the capacity of the soil to replenish the soil solution P need to be considered (Bolland *et al.*, 2001).

In most tropical and subtropical regions of the world, including Cameroon, phosphorus availability is highly limited due to the presence of oxides and hydroxides of aluminium and iron in these areas. When these oxides react with soluble phosphates found in the soil, they form complexes of low solubility which greatly reduces the amount of available phosphorus (Tsado *et al.*, 2012). From my point of view; phosphorus deficiency in plants constitutes the first most

important soil fertility problem throughout the world. Due to the fact that most farmers in Cameroon use phosphorus fertilizers to improve on their agricultural yields, it is necessary to find out the amount that is readily available to plants in order to avoid excesses and reduce water pollution by fertilizers (Tening *et al.*, 2013).

Phosphorus fixation is a term that is used to describe both P-sorption and P-precipitation. Since both P-sorption and P-precipitation reduce P availability, a soil with a great P-fixation capacity has less available P after fertilization than a soil with a low P-fixation capacity (Silva and Uchida, 2000). Tsado *et al.* (2012), Idris and Ahmed (2012) and Tening *et al.* (2013) reported that oxides and hydroxides of aluminium and iron, found on soil surfaces of soils are specific adsorption sites of P.

Plants may absorb P either as the primary monobasic phosphate, H_2PO_4^- ions or smaller amounts of the secondary dibasic phosphate, HPO_4^{2-} ions and the phosphate ion, PO_4^{3-} (Conklin, 2005). Adsorption isotherms can conveniently be described as the equilibrium relationships between the amounts of adsorbed and dissolved species of phosphate at constant temperature in quantitative terms. Phosphate adsorption isotherms are important criteria to study the interaction of the ions with the oxides and soil and have been used to measure the adsorption capacity of soils (Khan *et al.*, 2010). Adsorption is usually characterized by fitting the adsorption isotherm and their mathematical description using one or more adsorption equations (Zhang *et al.*, 2011).

The general objective of this study was to compare the P adsorptive capacity of four surface volcanic influenced soils of Foubot and understand their P adsorption mechanism by applying chemical analytical and theoretical principles. Specifically, this study was aimed to evaluate the phosphorus adsorption isotherms of surface horizons (0-20 cm) of the volcanic influenced soils of Foubot using four important equations which are: Freundlich, Langmuir, Temkin and Van Huay adsorption isotherms and to investigate the correlation between P adsorbed and some important soil physico-chemical properties and consequently recommend on the soil management practices in order to favour the availability of P to plants and control pollution.

MATERIALS AND METHODS

Description of the sampling site: Foubot is located in the Noun division of the West region of Cameroon. Soils from this area are soils with andic properties, having an accumulation of iron cemented on volcanic ash and humified horizon with mottling originating from basalt and micro granite complexes

(Makilo, 1982). The field work was carried out in mid March, 2014, with study site having two distinct climates (rainy and dry season). Four surface soils (0-20 cm) were collected from Mbankouop, Paponoun, Monoun and Baigom plain. In each site, a random sampling technique was used. The Mbankouop site is located at about 100 m away from "Ecole Publique de Mbambélé" on the right. The area had a slope of 5-6% (Clinometer-Recta), with an elevation of 1143 m above sea level, located on Latitude 05°38.500'N and Longitude 010°37.626'E (hand held Global Positioning System-GPS Garmin Etrex Vista C). The vegetation was characterised by the presence of *Pennisetum purperum* and *Emperata cylindrica*. The soil colour was 7.5YR 2.5/2, very dark brown at the surface (Munsell Colour, MI 49512). The Paponoun site had a slope of 6% and an elevation of 1152 m above sea level, located on Latitude 05°37.794'N and Longitude 010°37.940'E. The vegetation was characterised by the presence of *Pennisetum purperum* and *Chromolaena odorata*. The soil colour was GLEY1 2.5/10Y, greenish black at the surface. The Monoun site had a slope of less than 1%, an elevation of 1089 m above sea level and located on Latitude 05°34.515'N and Longitude 010°34.669'E. The area was currently being cultivated and the vegetation was characterised by the presence of *Arbustive savannah*. The soil colour was 2.5Y 2.5/1, black at the surface. The Baigom plain is located near mount Mbapit, had a slope of 5%, an elevation of 1118 m above sea level and located on Latitude 05°35.529'N and Longitude 010°43.084'E. The area was currently being cultivated and the vegetation was characterised by the presence of *Arbustive savannah*. The soil colour was grey 2.5/5B, bluish black at the surface.

Laboratory analysis: Freshly collected soil samples were air dried in the laboratory, ground in a porcelain mortar using a pistle and passed through a 2 mm sieve. The soil samples were then analysed for the various physico-chemical properties using international standard methods (Pauwels *et al.*, 1992) prior to sorption studies. All chemicals used in these analyses were of analytical grade.

The bulk density of the soils was determined over a soil volume of 100 cm³. Bulk density is the oven dry weight of soil per unit volume. It is expressed in g cm⁻³ and was calculated using the following Eq. 1:

$$\text{Bulk density} = \frac{\text{Mass of oven dry soil}}{\text{Volume of soil core}} \quad (1)$$

Soil pH was measured in a 1:2.5 soil: solution ratio in 1 N KCl (pH-KCl) and distilled water (pH-H₂O). Electrical Conductivity (EC) was determined after extraction with

distilled water in the ratio 1:5 with a conductimeter (WTW model). Exchangeable bases were determined by the method of Schollenberger by percolating 2.5 g of soil with 100 mL of 1N ammonium acetate, after which sodium and potassium ions were determined by flame photometry and calcium and magnesium ions estimated by complexometric titration. Cation Exchange Capacity (CEC) was estimated by percolating 2.5 g of soil with 100 mL of 1N ammonium acetate and then with 1N KCl, the collected NH₄⁺ ions were then determined by distillation and titration with a 0.01 N sulphuric acid. Total nitrogen was estimated by exploiting the Kjeldahl's distillation method while Soil Organic Carbon (SOC) was estimated by oxidation with potassium dichromate and titration with iron (II) sulphate (Walkley and Black, 1934). Particle size distribution was determined by Robinson-Köhn pipette method. Amorphous Fe and Al were determined colorimetrically after their reduction with ammonium oxalate in the dark, whereas free Fe and Al were determined colourimetrically after their reduction with Dithionate Citrate Bicarbonate (DCB). Available phosphorus was determined by Bray II method (Bray and Kurtz, 1945).

Phosphorus adsorption studies: Phosphorus adsorption isotherms were determined following the procedure of Rao (1993). Phosphorus solutions of 0, 1, 5, 10, 20, 40, 60 and 80 ppm were prepared using distilled water from a mother solution of ammonium dihydrogenophosphate, NH₄H₂PO₄ containing 1000 ppm P solution using the dilution formula. One gram of air dried soil samples were accurately weighed into 100 mL centrifuge tubes and 50 mL of each of the prepared solutions added to it and shaken for 24 h at 25°C on an end-to-end shaker (Edmund Buhler SM 25 model) at 125 oscillations per minute. The soil suspension was immediately filtered through a Whatman No. 2 filter paper and centrifuged at 3000 rpm for 30 min with a model HRT 20 MM multifunctional intelligent centrifuge in order to get the clear solution. One milliliter extract of each of the samples and blank was pipetted into test tubes and 2.5 mL of a mixture containing ammonium molybdate and sulphuric acid, 2.5 mL of ascorbic acid and 10 mL of distilled water were then added successively and mixed. The test tubes were thereafter put in a water bath at 85°C for 10 min to enhance colour development. After the blue colour must have developed, the P concentration was determined by colourimetry at a wavelength of 665 nm (Kuo, 1996). Each soil sample was analysed in duplicate. The quantity of P adsorbed by the soil (X) was calculated by the difference between the quantity of P initially present (C₀) and the quantity of P in the solution (C_e) after treatment using the following Eq. 2:

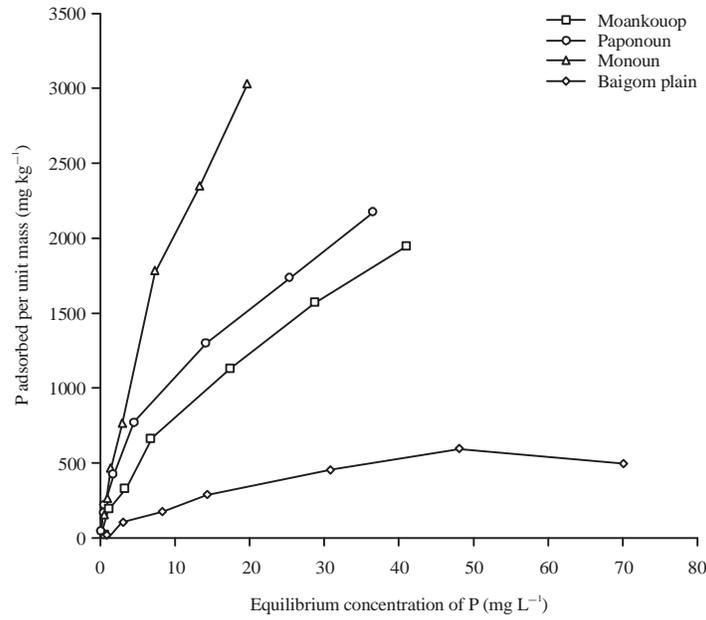


Fig. 1: Phosphorus adsorption isotherms of the soils

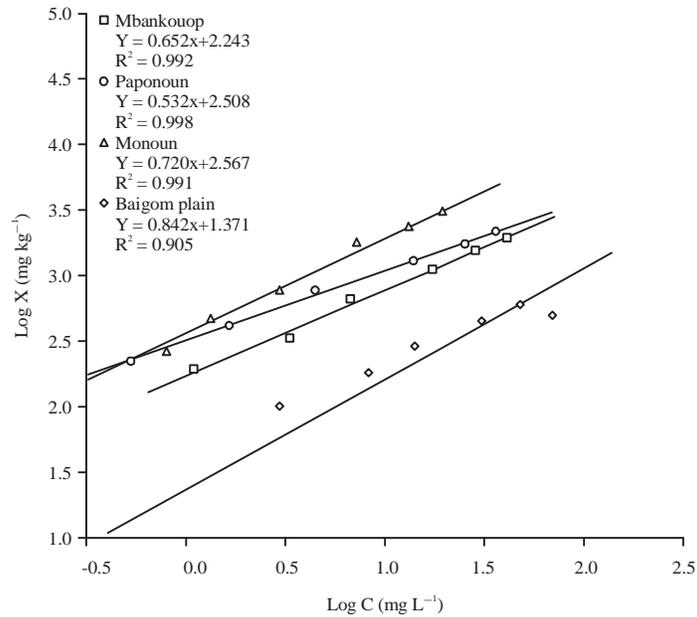


Fig. 2: Linear Freundlich adsorption isotherms of the soils

$$X = \frac{(C_o - C_e) \times V}{m} \quad (2)$$

Where:

V = Volume of P solution used

m = Mass of soil sample

The P adsorption data obtained was analyzed graphically by plotting P adsorbed as a function of equilibrium

concentration to give non linear adsorption isotherms (Fig. 1) and using linear isotherms of Freundlich, Langmuir, Temkin and Van Huay (Fig. 2-5) to transform the data from where adsorption coefficients were calculated.

The linear forms of the various adsorption isotherms are defined thus:

The Freundlich isotherm expresses the variation of an adsorbed quantity with equilibrium concentration (Sposito, 1984). The linear Eq. 3 will be as:

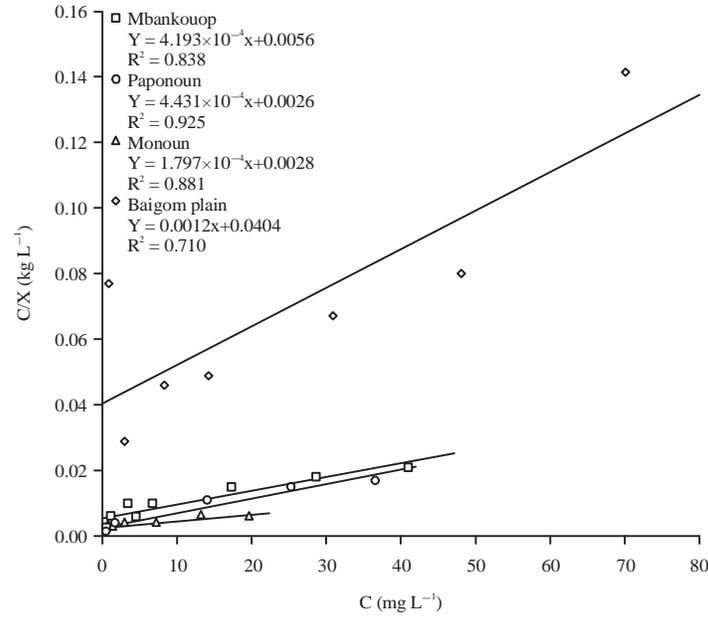


Fig. 3: Linear Langmuir adsorption isotherms of the soils

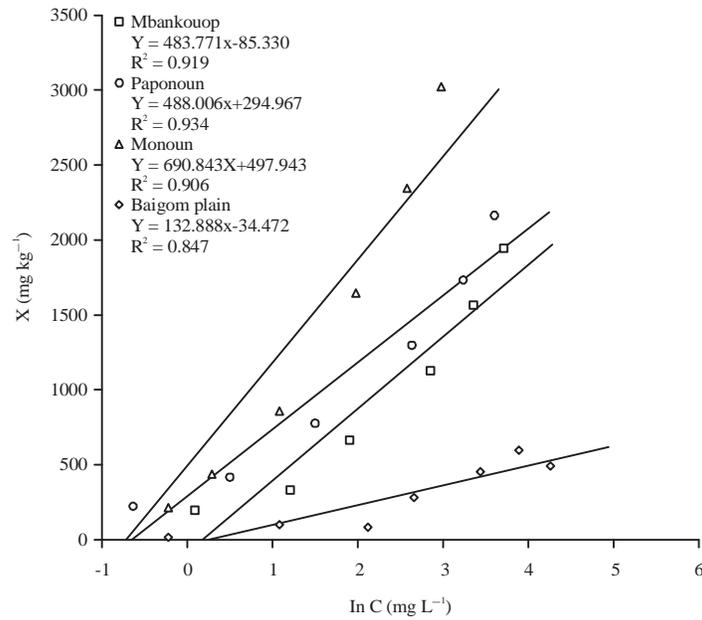


Fig. 4: Linear Temkin adsorption isotherms of the soils

$$\log X = \frac{1}{n} \log C + \log K_f \quad (3)$$

K_f = Adsorption equilibrium constant related to the boundary energy at the surface (mg kg^{-1})

Where:

- X = Amount of phosphorus adsorbed (mg kg^{-1})
- n = Constant whose value depends on the adsorbent
- C = Concentration of phosphorus in equilibrium solution (mg L^{-1})

Langmuir proposed his isotherm since 1918 to treat adsorption in gaseous phases and its linear equation for adsorption of solutes in solution is as Eq. 4:

$$\frac{C}{X} = \frac{C}{X_m} + \frac{1}{K_L X_m} \quad (4)$$

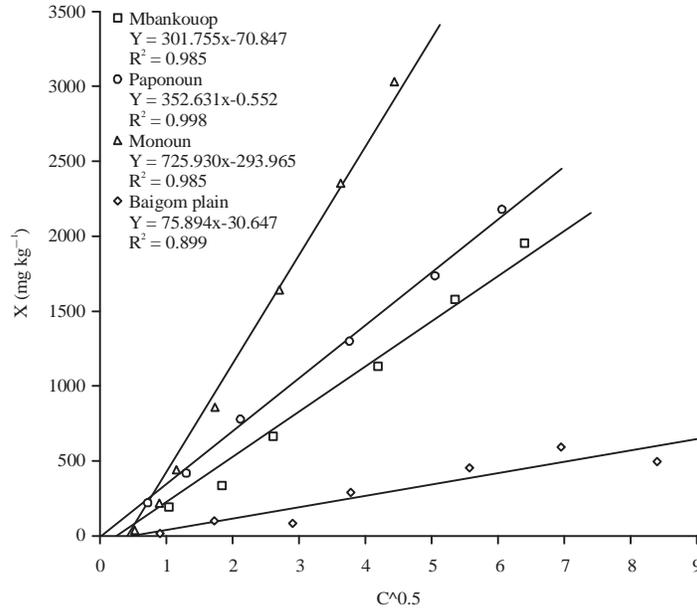


Fig. 5: Linear Van Huay adsorption isotherms of the soils

Where:

- X = Amount of phosphorus adsorbed (mg kg^{-1})
- X_m = Maximum adsorption capacity (amount of adsorbate needed for a monolayer coverage) (mg kg^{-1})
- K_L = Constant related to the boundary energy of the soil at the surface (L mg^{-1})
- C = Concentration of phosphorus in equilibrium solution (mg L^{-1})

- n = Van Huay adsorption coefficient (L kg^{-1})
- m = Van Huay constant parameter

Statistical analysis: Correlation and regression analyses were performed to relate some soil properties to P sorption characteristics. Correlation and regression analyses were performed using R software (R Development Core Team, 2009).

For the Temkin adsorption isotherm, the energy of adsorption is a linear function of the surface coverage (Travis and Etnier, 1981). The Temkin isotherm Eq. 5 is:

$$X = a + b \ln C \quad (5)$$

Where:

- a = Amount of P adsorbed of Temkin model (mg kg^{-1})
- b = Buffer capacity of Temkin model (mL g^{-1})
- X = Amount of P adsorbed (mg kg^{-1})
- C = Equilibrium solution concentration (mg L^{-1})

The Van Huay isotherm is defined as Eq. 6:

$$\frac{X}{m} = m + n\sqrt{C} \quad (6)$$

Where:

- X = Amount of phosphorus adsorbed (mg kg^{-1})
- C = Concentration in fluid phase (mg L^{-1})

RESULTS AND DISCUSSION

Some physico-chemical properties of the soils studied are depicted in Table 1 while, the phosphorus adsorption parameters are presented in Table 2. Simple linear correlation relationships (r) between soil phosphorus sorption parameters and some selected soil physico-chemical properties are shown in Table 3.

Results of physico-chemical analysis showed that all the four soil samples were moderately acidic with pH values ranging from 5.7-6.0. Most crops grow best when the soil pH is between 6.0 and 8.2 (Horneck *et al.*, 2011). When the soil is acidic, the availability of nitrogen, phosphorus and potassium is reduced (Silva and Uchida, 2000). This is probably because at low pH values, oxides and hydroxides of iron and aluminium become soluble and they tend to fix these nutrients. Soil pH can be increased by liming (the application of calcium carbonate or calcium hydroxide). The soil pH test indicates if lime is needed or not while the lime requirement test determines how much lime is needed (Horneck *et al.*, 2011;

Table 1: Selected physico-chemical properties of the soils studied (n = 2)

Soil series	pH-H ₂ O	pH-KCl	δpH	ρ (g cm ⁻³)	EC (μS cm ⁻¹)	OC (%)	OM (%)	N (%)	C/N	Avail. P (ppm)
Mbankouop	5.7	5.0	-0.7	0.90	40.0	4.80	8.28	0.21	22.34	9.37
Paponoun	6.0	5.1	-0.9	0.72	110.0	6.36	10.97	0.27	23.62	7.45
Monoun	6.0	5.1	-0.9	0.73	80.0	4.94	8.52	0.19	26.44	10.01
Baigom	5.8	5.1	-0.7	0.84	270.0	3.38	5.82	0.13	25.40	32.44

Soil series	Exchangeable bases (meq S/100 g)						Particle size (%)			Free and amorphous Al and Fe (mg g ⁻¹ soil)			
	CEC (meq/100 g)	Ca	Mg	Na	K	S	Sand	Silt	Clay	Al _f	Al _a	Fe _f	Fe _a
Mbankouop	14.40	7.68	4.72	0.04	0.02	12.46	13.9	78.0	8.1	5.00	0.00	3.70	0.82
Paponoun	26.80	4.16	7.60	0.40	0.02	12.18	26.2	66.8	7.0	3.30	0.59	2.35	0.82
Monoun	19.60	1.36	2.48	0.40	0.02	4.26	33.8	52.9	13.2	5.00	0.59	3.70	1.73
Baigom	16.00	7.76	6.24	0.40	0.02	14.42	3.0	79.5	17.5	2.50	0.59	8.25	0.37

δpH: Net charge, ρ: Bulk density, EC: Electrical conductivity, OC: Organic carbon, OM: Organic matter, N: Total Nitrogen, C/N: Mineralization factor, Avail. P: Available phosphorus, CEC: Cation exchange capacity, S: Sum of exchangeable bases, Al_f: Free aluminium, Al_a: Amorphous aluminium, Fe_f: Free Iron, Fe_a: Amorphous Iron

Table 2: Values of Freundlich, Langmuir, Temkin and Van Huay adsorption constants and multiple correlation coefficients of the soils

Soil series	Freundlich			Langmuir			Temkin			Van Huay		
	1/n	K _F	R ²	X _m	K _L	R ²	b	a	R ²	n	m	R ²
Mbankouop	0.65	174.99	0.992	2384.93	0.075	0.838	483.77	-85.33	0.919	301.76	-70.85	0.985
Paponoun	0.53	322.11	0.998	2256.83	0.170	0.925	488.01	294.97	0.934	352.64	-0.55	0.998
Monoun	0.72	368.98	0.991	5564.83	0.064	0.801	690.84	497.94	0.906	725.39	-293.97	0.985
Baigom	0.84	23.50	0.905	833.33	0.030	0.710	132.89	-34.47	0.847	75.89	-30.65	0.899

Table 3: Linear correlation (r) relationships between soil phosphorus sorption parameters and some selected soil properties of the soils (n = 7)

Soil properties	Freundlich		Langmuir		Temkin b	Van Huay n
	1/n	K _F	X _m	K _L		
pH-H ₂ O	-0.211NS	0.738NS	0.211NS	0.211NS	0.738NS	0.738NS
SOM	-0.800NS	0.800NS	0.400NS	0.800NS	0.800NS	0.800NS
Avail. P	1.000°	-0.400NS	-0.200NS	-1.000°	-0.400NS	-0.400NS
S	0.400NS	-1.000°	-0.800NS	-0.400NS	-1.000°	-1.000°
Silt	0.400NS	-1.000°	-0.800NS	-0.400NS	-1.000°	-1.000°
Fe _f	0.949*	-0.632NS	-0.316NS	-0.949*	-0.632NS	-0.632NS
Fe _a	-0.316NS	0.949*	0.949*	0.316NS	0.949*	0.949*

SOM: Soil organic matter, Avail. P: Available phosphorus, S: Sum of exchangeable bases, Fe_f: Free iron, Fe_a: Amorphous Iron, *Significant (p<0.05), °Significant (p<0.1), NS: Non significant

Spargo *et al.*, 2013). The soils had low bulk density values ranging from 0.72-0.90, which is typical of volcanic soils. The electrical conductivities of the soils were generally low and the values were less than 1000 μS cm⁻¹ which show that the soils are suitable for crop production in terms of EC as shown by Horneck *et al.* (2011) who reported that soils with EC values less than 1000 μS cm⁻¹ are suitable for crop production. The organic matter content was found to be average (5.82-10.97%) for all the soil samples. The total nitrogen content was very low in all the soils (N<1%). The C/N ratio for most of the soils was high (22.34-26.44) indicating that the organic matter content was poorly mineralised. The available phosphorus in the soils ranged from low to medium (7.45-32.44 ppm) with Baigom plain having the greatest value (32.44 ppm). Cation Exchange Capacity (CEC) which is a measure of the soil's ability to retain and supply nutrients (specifically the positively charged nutrient ions called cations) was high (14.40-26.80 meq/100 g) for all the soil series. The sum of the

exchangeable bases was average (4.26-14.42 meq/100 g) for the soils. Base saturation which is the percentage of the soil CEC that is occupied by basic cations (calcium, magnesium, potassium, sodium) at the current soil pH value was less than 100% for all the soils, a fact which shows that the soils studied are acidic in nature. Results of particle size analysis showed that some of the soils were silty-clay in texture (Baigom plain) with the silt component highly dominant. Paponoun and Monoun samples were sandy-loam in texture, with the silt component still highly dominant. The concentration of free and amorphous Al and Fe were low in most of the soils (0.00-8.25 mg g⁻¹ soil) with that of free Al and Fe greater than amorphous Al and Fe.

The phosphorus adsorption isotherms are shown in Fig. 1, while linear regression graphs showing regression equations and coefficients of determination (R²) for Freundlich, Langmuir, Temkin and VanHuay isotherms are presented in Fig. 2-5, respectively.

The adsorption isotherm graphs presented on Fig. 1 exhibited different curves showing that each soil sample adsorbs phosphorus differently. It was also observed that there were at least two adsorption phases for most of the soil samples. The first phase was rapid (adsorption of P) and the second phase was slow (converting P to more firmly held forms). This may correspond to the rapid adsorption phase and to the more firmly adsorbed phase according to Barrow (1978). According to Giles *et al.* (1960) and Weber (1970), these isotherms are of the L-type, showing that the soils have a high affinity for phosphorus. P adsorption was observed to be very high at the beginning and this value increased with an increase in the concentration of added P with maximum adsorption values of 497.90, 1949.12, 2174.04 and 3020.86 mg kg⁻¹ soil recorded for Baigom plain, Mbankouop, Paponoun and Monoun, respectively in an increasing order. Phosphorus adsorption characteristics of the soils shown in Table 2 indicated that there were differences in the sorption characteristics obtained from the different linear isotherms.

Freundlich parameters, that is, boundary energy of the soil at the surface (K_f), P sorption energy (n) and correlation coefficient values computed from the data plotted on Fig. 2 are shown in Table 2. The goodness of fit of the model was ascertained by looking at the R² values. All the plots were highly correlated with R² values >0.90, indicating apparent high conformity of the adsorption data to the Freundlich model. Generally, the Freundlich model seemed fit at all equilibrium concentrations. For all the soils, the values of sorption capacity (K_f) ranged from 23.50 mg kg⁻¹ for Baigom to 368.98 mg kg⁻¹ for Monoun and P sorption energy (n) from 0.53 L kg⁻¹ for Paponoun to 0.84 L kg⁻¹ for Baigom plain.

Langmuir parameters, that is, boundary energy of the soil at the surface (K_L), maximum adsorption capacity (X_m) and correlation coefficient values computed from the data plotted on Fig. 3 are shown in Table 2. All the plots were not highly correlated with R² values ranging from 0.710 to 0.925, indicating a non apparent high conformity of the adsorption data to the Langmuir model. Langmuir equation gave maximum adsorption values of 833.33, 2256.83, 2384.93 and 5564.83 mg kg⁻¹ for Baigom plain, Paponoun, Mbankouop and Monoun, respectively and the binding energy values ranged from 0.03 L mg⁻¹ for Biagom to 0.17 L mg⁻¹ for Paponoun. Comparison of Langmuir adsorption maxima values with those obtained from the sorption data showed that values obtained from Langmuir equation were greater than those obtained from sorption data. This shows that all adsorption sites were not occupied by the adsorbate. Similar results have been reported by Anghinoni *et al.* (1996),

Khan *et al.* (2010), Tsado *et al.* (2012) and Yaser and Rahim (2013). From the binding energy values obtained from the Freundlich and Langmuir equations, it was observed that for all the soil series, the higher the binding energy, the higher the amount of phosphorus fixed and vice versa.

Temkin parameters, that is, P adsorbed of Temkin model (a), buffering capacity of Temkin model (b) and correlation coefficient values computed from the data plotted on Fig. 4 are shown in Table 2. All the plots were highly correlated with R² values ≥0.90, indicating apparent high conformity of the adsorption data to the Temkin model. The buffering capacity of Temkin model (b) varied from 132.89 mL g⁻¹ for Baigom plain to 690.84 mL g⁻¹ for Monoun indicating that the higher the buffering capacity, the higher the sorption capacity of the soil and vice versa. These results conform to those of Sanyal *et al.* (1993), Dubus and Becquer (2001) and Khan *et al.* (2010).

Van Huay parameters, that is, Van Huay adsorption coefficient (n), Van Huay constant parameter (m) and correlation coefficient values computed from the data plotted on Fig. 5 are shown in Table 2. All the plots were highly correlated with R² values ≥0.90, indicating apparent high conformity of the adsorption data to the Van Huay model. The sorption coefficient (n) ranged from 75.89 L kg⁻¹ for Baigom plain to 725.39 L kg⁻¹ for Monoun, showing that the higher the Van Huay sorption coefficient, the higher the amount of phosphorus adsorbed and vice versa.

The highest value of adsorption for Monoun series may be due to its high amorphous iron and low available phosphorus content which greatly enhances phosphorus adsorption while the lowest value of adsorption for Baigom plain series may be due to its high available phosphorus and low amorphous iron content which does not favour phosphorus adsorption. Similar adsorption isotherms have been reported by Khan *et al.* (2010), Tsado *et al.* (2012), Idris and Ahmed (2012) and Tening *et al.* (2013).

Upon examining the accuracy of adsorption isotherms in predicting phosphorus adsorption, it was observed that accuracy increased in the following order: single surface Langmuir isotherm, Van Huay isotherm, Temkin isotherm and Freundlich isotherm.

It is expected that the P adsorption parameters be correlated with soil properties that are related to surface area such as clay and organic matter content and degree of weathering, especially pH and active forms of Fe and Al on the particle surfaces (Olsen and Watanabe, 1957; Stuanes, 1982; Anghinoni *et al.*, 1996). In this study, significant correlations (Table 3) were only found between the content of amorphous iron, free iron and Freundlich P sorption energy (n),

Freundlich's boundary energy of the soil at the surface (K_F), Langmuir P maximum adsorption (X_m), buffering capacity of Temkin model (b) and Van Huay adsorption coefficient (n) ($p < 0.05$) in spite of differences in the other soil properties such as pH, soil organic carbon, silk and clay contents of the soils. Other researchers (Sanyal *et al.*, 1993; Wendt *et al.*, 1993; Anghinoni *et al.*, 1996) were able to demonstrate the importance of oxides of iron in P adsorption by soils.

Lack of a significant correlation between P sorption parameters and one or more soil properties has been reported (Singh and Tabatabai, 1977; Kanabo *et al.*, 1978; Lewis *et al.*, 1981; Anghinoni *et al.*, 1996). The importance of organic matter, for instance, is ambiguous because it can act in two ways, either by sorbing P or by blocking sorption sites of inorganic particles (Stuanes, 1982). The soil samples used in this study were taken from different sites and therefore, are presumed different in the nature of organic matter. Stuanes (1982) reported that it is also difficult to separate the effect of single parameters in determining the P sorption capacity of soils, since they often are intercorrelated and also correlated with other parameters, active in P sorption as Fe and Al. In this study, significant positive correlations among such properties were found only between amorphous iron, free iron ($p < 0.05$) and weak negative correlations were found between available phosphorus, silk, sum of exchangeable bases ($p < 0.1$) and P adsorbed.

CONCLUSION

The adsorption isotherms showed different curves for each of the four soil series. The order for P adsorption followed a decreasing trend of Monoun > Paponoun > Mbankouop > Baigom plain. Insertion of sorption data into the various phosphorus adsorption models showed that the models were able to describe better the relationship between adsorbed phosphorus and phosphorus in equilibrium solution. Comparing the four equations (Freundlich, Langmuir, Temkin and Van Huay), it can be concluded that the accuracy of fitness of data of the four soil series into the equations increased in the order: single surface Langmuir isotherm, Van Huay isotherm, Temkin isotherm and Freundlich isotherm. In spite of the differences among soil properties related to surface area and degree of weathering of these soils, the content of amorphous and free iron were the only tested soil parameters that significantly correlated with constants of the isotherm equations. Results of this study revealed differences in P adsorption and identified amorphous iron, free iron, silk, available phosphorus and sum of exchangeable bases as the

main predictors of P activity in these soils. Although the P adsorption capacities of these soil series were low in some areas, Monoun soil requires more P fertilization than other soils for optimum crop production. Management practices involving routine soil testing for physical, chemical and mineralogical properties, the use of organic material and liming as a basis for P sorption reduction will be useful for crop production in Foubot.

ACKNOWLEDGMENTS

We wish to thank the farmers of Foubot for permitting us to use their fields for this study, the Head and technicians of LASAEC, FAAS for assisting us in field work and analysis and the anonymous reviewers of the submitted manuscript.

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