Full Length Research

Phosphorus fixation and its relationship with physicochemical properties of soils on the Eastern flank of Mount Cameroon

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The Eastern flank of Mount Cameroon is made up of human settlement and agricultural activities. Determination of phosphorus (P) fixation characteristics of soils around this region is important for a clean environment and economic fertilizer application. The objectives of this study were to evaluate P-fixation characteristics of soils within the region and identify factors contributing to P-fixation. Composite surface soil samples from five sites (between 36 to 1006 m) were collected and analyzed for physicochemical properties and P-fixation capacity. Fixation data were obtained by equilibrating the five soil samples with 25 ml of KH_2PO_4 in 0.01 M $CaCl_2$, containing 0, 10, 50, 100, 250 and 500 mg L^{-1}. Phosphorus-fixation data were fitted to Langmuir and Freundlich adsorption models and the relationship between P-fixation and soil properties was determined. The adsorption maximum (K_L) for Freundlich model was the highest for Limbe - Man O'War Bay Road (LMR, 174.58 mg P kg^{-1}), followed by SLR (34.12 mg P kg^{-1}), Dibanda-Mutengene Road (DMR, 24.72 mg P kg^{-1}), VAS and UPD (16.87 mg P kg^{-1}). The Langmuir adsorption maximum for Vasingi (VAS), Upper Boduma (UPD), Sasse-Limbe Road (SLR), DMR, and LMR were 0.01, 0.02, 0.01, 0.02 and 0.05 mg P kg^{-1}, respectively. The phosphate adsorption isotherm gave good fit adopting Freundlich (r = 0.98 to 0.99). K_F correlated with pH (r = - 0.87), Ca (r = - 0.87), exchange acidity (r = 0.87), and clay (r = 0.67). This study illustrated that P sorption isotherm in relation to soil properties can be used as a tool for P management in sustainable crop production.

Key words: Phosphorus fixation, adsorption isotherms, soil physicochemical properties, volcanic soils, Mount Cameroon.

INTRODUCTION

Phosphorus plays a very vital role in plant germination, growth and maturation. The chemistry of soil inorganic P strongly depends on the composition and crystalline nature of the solid phase of soils and the ionic nature of soil solution P (Mehmood et al., 2010). In most agricultural farms, the composition and crystalline nature

of the solid phase of soils, and the ionic nature of soil solution P vary greatly; this variation influences the chemistry of soil P and has drawn the attention of many researchers. Diverse techniques have been proposed to evaluate the status of P in the soil in a bid to advice on a better fertilizer management programme (Baskaran et al., 1994; Bolan and Baskaran, 1996; Muindi et al., 2015). The availability of P for plant uptake and its utilization are not a function of its concentration in the soil but rather a function of its release from soil surface into soil solution (Muindi et al., 2015). Fixation is said to have occurred when chemicals accumulate at the interface between solid phase and aqueous solution phase. This phenomenon determines the availability of native soil nutrients and the rates at which nutrients are applied to the soil as fertilizers. Phosphorus fixation has been defined by many researchers as a process in which phosphate ions are held on active sites of soil particle surfaces (Idris and Ahmed, 2012; Melenya et al., 2015). Phosphate ions are chemically unstable in soil solution, and readily react largely with oxides and hydroxides of aluminium (Al) and iron (Fe) found on clay surfaces for acidic soils and with the hydroxide of calcium (Ca) in calcareous soils to form less and more stable compounds (Bolan and Baskaran, 1996; Bolland et al., 2003).

Adsorption isotherms have been identified as an important criterion to estimate P concentration in aqueous phase of soil, energy of P adsorption and maximal adsorbed P by the soil (Gichangi et al., 2008; Hadgu et al., 2014), and identify the soil attributes responsible for P adsorption (Muindi et al., 2015). Isotherms can quantitatively describe the equilibrium relationship between the amount of adsorbed and dissolved phosphate at constant temperature (Muindi et al., 2015). Agbenin and Tiessen (1994) reported Langmuir maximum adsorption parameter, which significantly and positively correlated with soil properties such as clay, organic carbon, Fe and Al contents.

Several adsorption models (such as Langmuir, Freundlich, Tempkin, and Van Huay adsorption models) have been proposed to describe and quantitatively measure phosphate adsorption. The Freundlich and Langmuir models are the most popular models because they have been reported to give the best fits (Niang et al., 2002; Hadgu et al., 2014; Muindi et al., 2015).

Anghiononi et al. (1996) and Mehmood et al. (2010), reported positive correlations between adsorbed P and soil properties such as texture, organic matter, soil pH, aluminium saturation, cation exchange capacity (CEC), oxides of Al and Fe. Great attention should be given to any soil property that correlates positively with adsorbed P because increasing this soil property will increase adsorbed P and reduce plant available P.

Agriculture is the main activity carried out by most of the inhabitants of the Mount Cameroon region. The soils from this region are generally low in available P (Tening et al., 2013). Knowledge of the relationship between soil properties with P-fixation is necessary for the effective application of phosphorus fertilizer on varied soils on the Eastern flank of Mount Cameroon region. Tening et al. (2013) reported that P-fixation capacity correlated positively with clay content and pH, and negatively with organic carbon and available P in some soil horizons that were collected from a soil profile within this region. They also observed that between 52 and 99% of P is fixed by the surface soil horizon in this area a day after P application. Notwithstanding, very limited work has been carried out on varied agricultural surface soils to understand the relationship between the P-fixation capacity and specific soil properties.

The adsorption models have not been used around the Mount Cameroon region probably because no research work has focused at quantifying the amount of P retained by these soils. Here, attempt was made to use Langmuir and Freundlich adsorption models to characterize phosphorus fixation around the Mount Cameroon region and relate it to some soil attributes.

The objectives of this study were therefore to investigate the relationship between P-fixation capacity and soil properties within the sub region and to compare the applicability of Langmuir and Freundlich isotherm equations in describing the P-fixation in soils in the sub region.
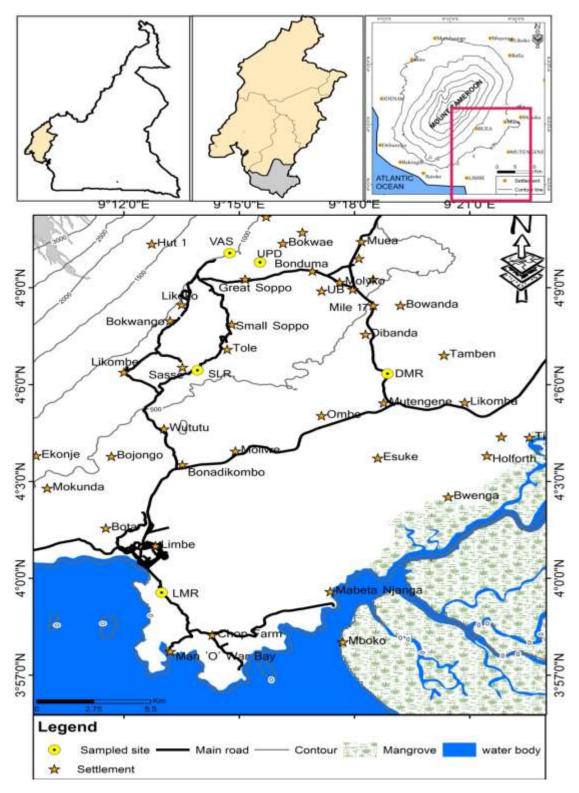
MATERIALS AND METHODS

Location of study area

The study area lies on the lower slopes of the Eastern flank of Mount Cameroon, the highest mountain (4095 m) in West and Central Africa. Mount Cameroon, an active volcano with eight eruptions reported since the beginning of the 20th century, is located or lies within latitudes 4° 00'-4°13'N and longitudes 9°00' – 9°30'E (Figure 1). The climate of the Eastern slopes of Mount Cameroon is humid tropical. The former is characterized by a distinct dry season (mid-November to March) and rainy season (mid-March to November). Climatic conditions such as temperature (26 to 29°C), and annual rainfall (3000 to 4000 mm) (Manga et al., 2013) promote the growth of abundant vegetation on Mount Cameroon. The colonization of the Mount Cameroon basaltic deposits by grass, shrubs or trees, and a rain forest at about 2000 m is controlled by elevation and rainfall. A fivefold increase in weathering rates from high to low elevations in this area was observed by Benedetti et al. (2003). They attributed this to the role of vegetation, temperature and rainfall at lower elevations.

The soils of this region are developed from the weathering of a

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Figure 1. Location and sample distribution map. Inset is the map of Cameroon showing the SW Region, Mount Cameroon and Mount Cameroon with a zoom on the study area.

basaltic parent rock (Manga et al., 2013). These soils have been intensely weathered in some areas to produce well drained to clayey reddish brown and yellowish soils which are over 10 m thick.

Yet in other areas, the soils are well drained, relatively young black soils developed from protracted weathering of basalticaa and pahoehoe lava flows. A lot of work has been carried out on the
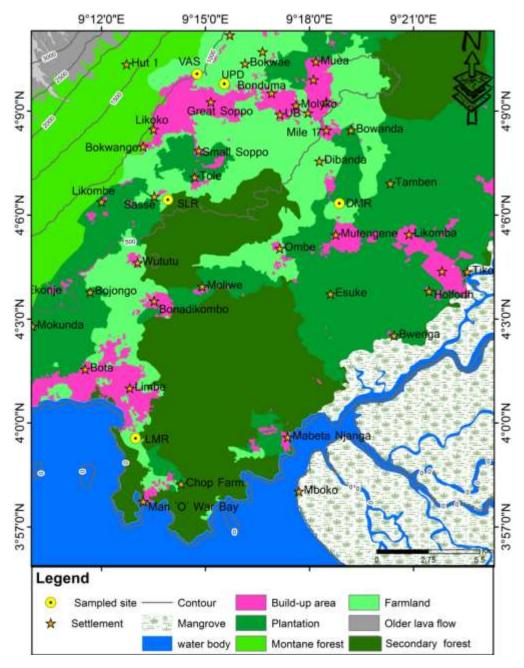
Figure 2. Land cover map of the study area. Note the presence of vast plantations and secondary forest.

toposequence of soils along the slopes of volcanoes to assess the effect of climate on weathering and mineral formation (Zehetner et al., 2003; Soubrand-Colin et al., 2007; Manga et al., 2013). The authors used parameters such as number of horizons, thickness of B-horizon characterized by altitudinal and climatic variability to evaluate degrees of soil formation. Manga et al. (2016) showed that the weathering status (derived from chemical weathering indices) of soils along the slopes of Mount Cameroon showed that the most weathered profiles are located at the higher elevations with lower mean annual precipitation.

Five sampling sites were selected at different elevations and agro-ecological zones along the Eastern slopes of Mount Cameroon (Figure 2 and Table 1). Surface soil samples (0 to 20 cm) were collected from these sites, air-dried, ground and passed through a 2-mm stainless steel sieve. Soil pH and electrical conductivity (EC) were measured in 1:5 soil to water ratio, bulk density and moisture content were determined following the oven-dry method. Organic carbon (%C) was determined by Walkley and Black wet combustion method described in Dhyan et al. (2005) and organic matter (OM) was calculated from the levels of organic carbon in the soil by multiplying by 1.72 as reported in Hazelton and Murphy (2007). Exchangeable bases were determined following the Schollenberger method using a 1 M ammonium acetate solution buffered at pH 7 described in Benton (1999). Exchange acidity was

Table 1. Location and altitudes of soil sampling sites within the Eastern flank of Mount Cameroon.

Sample site	Sample code	Latitude	Longitude	Altitude (m)	Human activity
Vasingi	VAS	04° 10'4.6"N	009° 14'45.3"E	1006	Plantain farm
Upper Boduma	UPD	04° 09'47.3"N	009° 15'32.5"E	786	Maize, beans and cassava farm
Sasse-Limbe Road	SLR	04° 06'26.6"N	009° 13'54.9"E	603	Maize, beans and cassava farm
Dibanda-Mutengene Road	DMR	04° 06'20.4"N	009° 18'51.7"E	351	Plantains, maize, beans and cassava farm
Limbe-Man O'War Bay Road	LMR	03° 59'33.5"N	009° 12'58.9"E	36	Cassava and maize farm

determined after the unbuffered KCl solution according to procedures described by Benton (1999). Cation exchanged capacity (CEC) was determined by a direct continuation of the Schollenberger's method using a 1 N KCl solution for displacement of ammonium ions. Effective cation exchange capacity (ECEC) was determined by summation (Sum of the exchangeable bases and exchange acidity). Available P was determined by Bray I method (Dhyan et al., 2005). Total nitrogen (%N) was determined by exploiting the Kjeldahl's distillation method (Dhyan et al., 2005). Total soil P was extracted using microwave assisted aqua regia digestion technique, the digested sample was mixed with Bray I extracting solution and total P in the extract was determined as reported by Murphy and Riley (1962). The distribution of particle sizes larger than 75 µm was determined by dry sieving and the distribution of particles smaller than 75 µm was determined by means of sedimentation process using a hydrometer method used to determine particle size according to ASTM D-422-63(1998) standard methods. To have an idea about the type of clay minerals present in these soil samples, soil activity was determined from Atterberg limits (liquid limit, plasticity limit and plasticity index) measured according to ASTM D 4318-10 (2010) standard methodology. Porosity was calculated from the bulk density and particle density (Brady and Weil, 1996):

$$f = 1- (\rho b/\rho s) \tag{1}$$

Where f = total porosity, ρb = bulk density, ρs = particle size density (2.65 g/cm³) a standard value as stated in Hazelton and Murphy (2007).

In the fixation study, about 5 g air-dried soil samples were weighed, in triplicates, into 50 ml polypropylene centrifuge tubes and equilibrated with 25 ml of KH_2PO_4 in 0.01M $CaCl_2$ containing 0, 10, 50, 100, 250, and 500 mg P/L. Two drops of chloroform were added to each tube to act as a microbial inhibitor. The tubes were set in a mechanical shaker for 16 h at 120 turns/min. Following equilibration, the soil suspensions were centrifuged at 4000 rotations/min for 20 min and filtered through Whatman No.5 filter paper to obtain a clear solution. The inorganic P was determined by the phosphomolybdate blue method of Murphy and Riley (1962). The amount of P fixed by the soil (P_{ads}) was calculated from the difference between the initial concentration (P_o) and the equilibrium concentration (P_{eq}) which is P remaining in soil solution. Phosphorus-fixation data for the soils used in this study were fitted into the linearized form of the Langmuir and Freundlich equations proposed by Muindi et al. (2015).

The Langmuir's equation described in its linear form is:

$$\frac{C}{X} = \frac{1}{K_L b_L} + \frac{C}{b_L} \tag{2}$$

The Freundlich's equation described in its linear form is:

$$\log X = \log K_F + n_F \log C \tag{3}$$

where C = Equilibrium concentration of phosphorus in solution (mg P L⁻¹), X = mg of P adsorbed (mg P kg⁻¹), b_L= Adsorption maximum for Langmuir model(mg P kg⁻¹), K_L= Bonding energy constant of Langmuir model (L mg⁻¹P), n_F = Empirical constant related to bonding energy of soil for phosphate, and K_F= Proportionality constant for Freundlich model (mg P kg⁻¹).

The phosphate adsorption isotherms of soils in the five study sites were determined by plotting the equilibrium concentration of phosphate (C) against the amount of phosphate fixed (X).

The sorption isotherms were examined according to the linear form of the Langmuir and Freundlich equations. Langmuir adsorption isotherms were plotted (Equation 2) by taking C (mg P L⁻¹) as X-axis against C/X (kg L⁻¹) as y-axis. The adsorption isotherm was equally examined by the linear form of the Freundlich equation (Equation 3) by plotting log C against log X.

RESULTS AND DISCUSSION

Physical properties

The five soils have a bulk density values varying from 0.67 to 1.01 g/cm³. VAS had the lowest (0.67 g/cm³), followed by Upper Boduma (UPD) and Sasse-Limbe Road (SLR, 0.84 g/cm³), Limbe - Man O'War Bay Road (LMR, 0.96 g/cm³), and the highest with Dibanda-Mutengene Road (DMR, 1.01 g/cm³) (Table 2). Olafur (2008) reported that volcanic ash soils generally have bulk density less than 0.9 g/cm³; therefore our values show that these soils are typically volcanic ash soils.

Particle size fraction indicates that the textural class of the surface composite soil samples ranged from loam (VAS), through clayey loam (UPD, SLR and LMR) to silty clay (DMR). In all the soils, silt fraction has dominant except for the LMR sample where the clay fraction dominated. Generally, we can say silt content > clay content > sand content (Table 2). This was clearly reflected by their corresponding total porosity values with the silty clay soil having the least porosity (0.62) and the loamy soil having the highest porosity (0.75). Clay is the most active part of the soil both chemically and physically (Page, 1952). The chemical properties of a soil are favorable when clays are abundant but its physical properties will either be good or poor depending on the arrangement of the soil particles (Page, 1952).

The moisture content of a soil is an important soil property in agriculture especially if it is interpreted with

Table 2. Some physical properties of soils from the five sites on the Eastern flank of Mount Cameroon.

Sample code	Soil colour	Bulk density (g/cm³)	Moisture content (%)	Total porosity	Particle size distribution			Textural class*	Atterberg's activity
					Sand (%)	Silt (%)	Clay (%)		
VAS	2.5YR3/4	0.67	36.14	0.75	41.2	42.0	16.8	L	0.3
UPD	5YR3/2	0.84	31.78	0.68	24.8	45.8	29.4	CL	0.3
SLR	5YR3/2	0.84	21.79	0.68	23.0	41.9	35.1	CL	0.2
DMR	5YR3/2	1.01	19.01	0.62	19.6	40.0	40.4	SC	0.2
LMR	2.5YR8/6	0.96	28.28	0.64	29.4	32.1	38.5	CL	0.3

*CL: Clay loam; SC: Silty clay; L: Loam.

Table 3. Some chemical properties of soils from the five sites on the Eastern flank of Mount Cameroon.

Sample code	pH (H₂O)	EC	Total N	OM	Total P	Bray I P	Ca	Mg	K	Na	Exch. acidity	ECEC	Exch. Fe	CEC
		(uS/cm)	%		mg kg⁻¹						cmol(+) kg⁻¹			
VAS	5.6	38	0.22	5.04	602.4	7.9	8.65	4.32	1.91	0.11	0.68	15.67	0.17	21.82
UPD	5.3	19	0.14	3.01	813.2	6.8	4.52	1.65	0.07	0.13	0.14	6.51	0.15	17.07
SLR	5.2	22	0.20	4.40	800.2	7.2	3.96	1.77	0.07	0.10	0.87	6.77	0.16	14.44
DMR	4.8	24	0.15	3.30	629.5	3.6	3.13	2.01	0.09	0.10	1.13	6.46	0.16	14.54
LMR	4.7	18	0.16	3.47	1116.4	3.6	2.01	1.47	0.19	0.13	1.28	12.07	0.06	18.59

respect to the soil textural class. Of the five soil samples analyzed, that from Vasingi (VAS), a loamy soil, had the highest moisture content (36.14%) followed by UPD, a clay loamy soil (31.78%). These two sites had moisture contents, which were above field capacity when compared with the standard soil moisture range chart (Zotarelli et al., 2010), and if exceeded, can lead to landslides especially the sample UPD which is clay loam and had a total porosity of 0.684. LMR which is a clay loamy soil, had 28.28% moisture content and is known to be at field capacity with good agricultural potential. SLR a clay loamy soil with moisture content 21.79% is at its irrigation start point (Zotarelli et al., 2010). During farming seasons, irrigation is encouraged in this soil else plants will eventually start wilting. DMR is a clayey soil with moisture content 19.01% is at wilting point (Zotarelli et al., 2010), and hence immediate irrigation is recommended for farmers cultivating this area else crop will die at early stage.

Chemical properties

Soil pH (H₂O) of composite surface samples from this region ranged from 4.7 to 5.6 (Table 3). The LMR soil had the lowest pH of 4.7 while the VAS soil had the highest pH of 5.6. All composite surface soils from this region based on their pH (H₂O) are in the range of strongly acidic as per ratings by Benton (1999). The acidity of these soils may be associated with the high rain

fall, coupled with the porous nature of the soils, resulting in leaching of bases. Based on the acidic nature of these soils, phosphate ions from P fertilizers often applied to soils of this nature could combine with Al and Fe to form aluminium and iron phosphates, respectively, which are known to be insoluble (Dhyan et al., 2005). There is an increase of pH with altitude which could be attributed to the decrease in temperature with altitude leading to decrease in rainfall. With low rainfall, the exchangeable bases are not washed away thereby increasing the pH.

Electrical conductivity (EC) ranged from 18 to 38 µS/cm (Table 3). According to the ratings established by Hazelton and Murphy (2007), EC was very low for all samples. Low range of EC indicates that tolerant crops and sensitive crops will not be affected if cultivated in these soils.

Vasingi (VAS) soils had the highest percent organic matter (5.04%) and DMR the lowest (3.30%). All the soil samples were in a high organic matter range as per ratings established by Hazelton and Murphy (2007). The soil organic matter content of the composite surface soils from the South Eastern flank of Mount Cameroon positively correlated to the available phosphorus (r = 0.67, P < 0.05) and exchangeable Fe (r = 0.62, P < 0.05) (Table 5). This positive correlation existing between organic matter and plant available phosphorus may be because soil organic matter (SOM) among other soil properties has been known to constituent the soil sorption complex which is responsible for binding of anions in the soil material (Tan, 1986). Cation exchange capacity

(CEC) in all soils was in the range of medium as per ratings established by Hazelton and Murphy (2007). CEC ranged between 14.44 cmol (+) kg^{-1} for SLR soil and 21.82 cmol (+) kg^{-1} for VAS soil (Table 3). CEC positively correlated to the effective cation exchange (ECEC) (r = 0.70, P < 0.05) and moisture content (r = 0.80, P < 0.05) (Table 5). The positive correlation between CEC and ECEC is due to the fact that CEC is the main constituent of ECEC. The positive correlation existing between CEC and moisture content may be due to the fact that a moist soil can easily leach its bases. The moderate CEC may be associated to the high organic matter content in these soils as organic matter is a source of negative charge in the soil. Landon (1991) attributed high soil fertility and high nutrient retention capacity to high CEC and low soil fertility, poor nutrient retention capacity to low CEC; therefore these composite surface soil samples are moderately fertile and moderate in nutrient retention capacity.

The ECEC ranged between 6.46 cmol (+) kg^{-1} and 15.67 cmol (+) kg^{-1} (Table 3) with VAS having the highest ECEC value (15.67cmol (+) kg^{-1}) and DMR the lowest (6.46 cmol (+) kg^{-1}). The desired range for ECEC is between 5 and 25 cmol (+) kg^{-1} Landon (1991). Therefore, ECEC was in the desirable range for all soils and is normally satisfactory for agriculture with average fertilizer application. One reason for the moderate ECEC may be that there is enough ionization of the functional groups of the OM to develop a great number of negative charges. Another possibility is that a great part of the organic charges might not have strongly interacted with the inorganic fraction, decreasing the effective negative charge. Both CEC and ECEC are moderate and positively correlated with each other (r = 0.70, p < 0.05). This may be due to the fact that very few portions of the exchangeable sites were occupied by exchangeable Al as a result of weathering and leaching that has occurred.

Exchangeable bases (Ca^{2+}, Mg^{2+}, K$^+$, Na$^+$) in all composite surface soil samples showed the following trend: Ca^{2+} > Mg^{2+} > K$^+$ > Na$^+$. Quantitatively, the concentrations of these cations vary as follows: Ca^{2+} (between 2.01 and 8.65 cmol (+) kg^{-1}), Mg^{2+} (between 1.47 and 4.32 cmol (+) kg^{-1}), K$^+$ (between 0.07 and 1.91 cmol (+) kg^{-1}), and Na$^+$ (between 0.10 and 1.13 cmol (+) kg^{-1}) (Table 3). These concentrations are quite low (especially for K$^+$ and Na$^+$), low for Mg^{2+} and vary from low to medium for Ca^{2+} based on the ratings established by Hazelton and Murphy (2007). These low concentrations may be as a result of the porous nature of the composite surface samples that are prone to base leaching. These low concentrations can also be explained from the prevalence of pH values of less than 5.5, where these cations are deficient (Kim, 1998). Nevertheless, Ca^{2+} is in moderate concentrations for VAS soil with respect to the critical fertility levels.

Vasingi soils registered the highest value of available P (Bray 1) with 7.8 mg P kg^{-1} whereas DMR and LMR had the lowest 3.6 mg P kg^{-1} available P (Table 3). All samples from the study area were in the range of low available plant phosphorus as per ratings established by Hazelton and Murphy (2007). These low P concentrations may be associated with the acidic nature of the soils: all the soils studied are strongly acidic with pH values <5.5. Harrison (2007) reported that at this pH values, Al, Fe and Mg are highly soluble and will react with the phosphate ions (H$_2$PO$_4^-$) to form hydroxyl-phosphate which is insoluble, and unavailable for plants. The low contents of available P observed in the soils of the study area were in agreement with the studies made by Tening et al. (2013) on soils collected within this region.

From the Atterberg limits and soil activity index, which is only an indication of the type of clay mineral present, all samples are likely to be dominated by kaolinite clay minerals (1:1 clay type), inactive and non-expanding clays (Skempton, 1969), as a result, if these soils could retain P, fixation will be described as being more a physisorption than a chemisorption phenomenon.

Phosphorus adsorption

The graphical representation of equilibrium P concentration versus rate of P adsorbed on unit mass of soil colloid were used to calculate the maximum adsorption capacity of the soils and the affinity of the soil to retain P. In all five soils, the equilibrium P solution and the per unit P adsorption by soil colloids increased with increasing P addition. The variation of the equilibrium concentration and the P adsorbed at each different levels of P is as shown in Figure 3.The graphic representation of the adsorption isotherms (Figure 3) of the soils showed that all samples respected the first order isotherm. This is a good confirmation to the choice of our isotherm models (Langmuir and Freundlich isotherm models) which obey the first order isotherm.

Linearizing the adsorption data into different isotherm models

The phosphorus adsorption maxima were determined by fitting the solution P concentrations and adsorbed P values in Langmuir and Freundlich equations. The highest P adsorption maxima (Table 4) for the five composite surface soils according to Langmuir (b$_L$) followed the order VAS (0.01 mg kg^{-1}) < SLR (0.01 mg kg^{-1}) < DMR (0.02 mg kg^{-1}) < UPD (0.02 mg kg^{-1}) < LMR (0.05 mg kg^{-1}) and according to Freundlich (K$_F$) followed the order VAS and UPD (16.87 mg kg^{-1}) < DMR (24.72 mg kg^{-1}) < SLR (34.12 mg kg^{-1}) < LMR (174.58 mg kg^{-1}). The phosphate adsorption isotherms gave a good fit in case of Langmuir (r^2 = 0.91 to 0.99) and Freundlich (r^2 = 0.98 to 0.99) obtained from their equations derived from Figures 4 and 5 are as shown in Table 4. The uniqueness
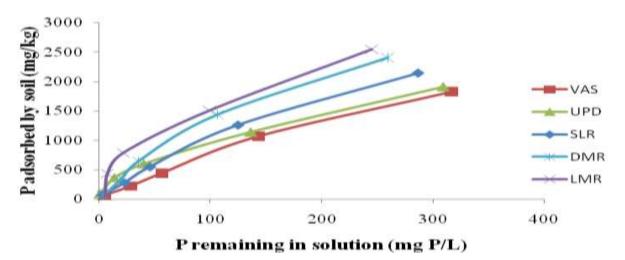
Figure 3. Phosphate adsorption plots of soils from the five sites on the Eastern flank of Mount Cameroon.
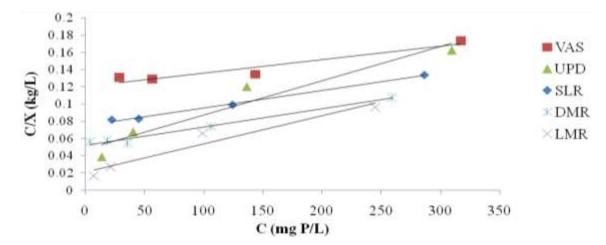

Figure 4. Phosphate adsorption fitted into Langmuir equation for soils from the five sites on the Eastern flank of Mount Cameroon.
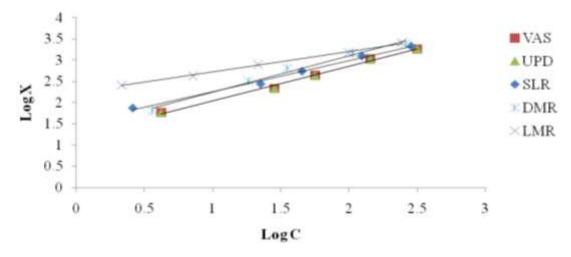

Figure 5. Phosphate adsorption fitted into Freundlich equation for soils from the five sites on the Eastern flank of Mount Cameroon.

Table 4. Parameters of fitted Langmuir and Freundlich adsorption models for five sites on the eastern flank of Mount Cameroon.

Parameter	Langmuir isotherm			Freundlich isotherm		
	b_L	K_L	R^2	K_F	n_F	R^2
VAS	0.008	1000	0.911***	16.866	0.813	0.993***
UPD	0.021	1000	0.930***	16.866	0.813	0.993***
SLR	0.014	1000	0.995***	34.119	0.729	0.993***
DMR	0.019	1000	0.978***	24.717	0.857	0.978***
LMR	0.050	1000	0.944***	174.582	0.480	0.997***

***Significant at $P \leq 0.001$ level.

Table 5. Correlation coefficient (r) between some soil physicochemical properties.

Correlation	pH	EC	Total N	OM	Total P	Bray1 P	Ca	Mg	K	Na	Exch. acid	ECEC	CEC	Exch. Fe	clay	Bulk density	Moisture
pH	1.00																
EC	0.60*	1.00															
Total N	0.30	0.50	1.00														
OM	0.30	0.50	1.00**	1.00													
TotP	-0.60*	-1.00**	-0.50	-0.50	1.00												
Bray1P	0.87*	0.56	0.67*	0.67*	-0.56	1.00											
Ca	1.00**	0.60*	0.30	0.30	-0.60*	0.87*	1.00										
Mg	0.60*	1.00**	0.50	0.50	-1.00**	0.56	0.60*	1.00									
K	0.05	0.36	0.56	0.56	-0.36	0.11	0.05	0.36	1.00								
Na	0.00	-0.63*	-0.32	-0.32	0.63*	-0.16	0.00	-0.63*	0.16	1.00							
Exch. acid	-0.90**	-0.30	0.10	0.10	0.30	-0.67*	-0.90**	-0.30	0.31	-0.16	1.00						
ECEC	0.30	0.10	0.80*	0.80*	-0.10	0.56	0.30	0.10	0.67*	0.32	0.00	1.00					
CEC	0.30	0.10	0.30	0.30	-0.10	0.21	0.30	0.10	0.82*	0.63*	-0.10	0.70*	1.00				
Exch. Fe	0.67*	0.98**	0.62*	0.62*	-0.98**	0.71*	0.67*	0.98**	0.29	-0.65*	-0.36	0.21	0.05	1.00			
clay	-0.90**	-0.30	-0.40	-0.40	0.30	-0.87*	-0.90**	-0.30	-0.15	-0.32	0.80*	-0.60*	-0.50	-0.41	1.00		
Bulk density	-0.87*	-0.36	-0.56	-0.56	0.36	-0.95**	-0.87*	-0.36	-0.16	-0.16	0.72*	-0.67*	-0.41	-0.50	0.98**	1.00	
Moisture	0.70*	0.10	0.30	0.30	-0.10	0.62*	0.70*	0.10	0.41	0.63*	-0.60*	0.70*	0.80*	0.15	-0.90**	-0.82*	1.00
Total porosity	0.87*	0.36	0.56	0.56	-0.36	0.95**	0.87*	0.36	0.16	0.17	-0.72*	0.67*	0.41	0.50	-0.98**	-1.00**	0.82*

*Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed).

Table 6. Correlation coefficient between Freundlich parameters and soil physicochemical properties.

Correlation	k_F	n_F
pH	-0.87[*]	0.36
EC	-0.56	0.67[*]
Total N	0.10	-0.31
OM	0.10	-0.31
Total P	0.56	-0.67[*]
Bray1P	-0.53	0.00
Ca	-0.87[*]	0.36
Mg	-0.56	0.67[*]
K	-0.03	-0.03
Na	-0.08	-0.41
Exch. acidity	0.87[*]	-0.36
ECEC	0.05	-0.56
CEC	-0.31	-0.10
Exch. Fe	-0.53	0.53
clay	0.67[*]	0.05
Bulk density	0.55	0.13
Moisture content	-0.56	-0.15
Total porosity	-0.55	-0.13

*Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed). n_F = Empirical constant related to bonding energy of soil for phosphate; K_F = Proportionality constant for Freundlich model (mg P/kg).

of Langmuir bonding energy constant (K_L) for all the composite surface soils (Table 4) and (r^2 = 0.91 to 0.99) compared with the corresponding Freundlich parameters, it could be said that Freundlich model better described P fixation in these soils more than Langmuir. This assumption can further be confirmed based on the display of points in Figure 4 for Langmuir and Figure 5 for Freundlich plots. Figure 4 shows that except for the SLR soil sample, the linearized data according to Langmuir model produced curves than straight lines and this was contrary to Figure 5 where the linearized data according to Freundlich, both samples gave straight lines. The b_L values < 1.0 mg kg^{-1} and Freundlich bonding energy constant (n_F) varied between 0.48 and 0.86 L mg^{-1}. These n_F values were similar to those reported in Ali et al. (2013).

Relationship between adsorption and soil physicochemical properties

Significant correlations were observed between Freundlich maximal adsorbed P and some soil physicochemical properties. There a negative correlation between K_F and soil pH (H_2O) (r = - 0.87, p < 0.05), this may be due to the fact that an increase in pH in acidic soils reduce the solubility of exchangeable Al adsorption sites and will eventually reduce the amount of soil P adsorbed, hence K_F. K_F negatively correlated with calcium as a lone soil exchangeable base (r = - 0.87, p < 0.05), this may be because among soil exchangeable bases, only Ca can react with the phosphates to form calcium phosphates but this was not the case here since the soils were strongly acidic and the concentration of Ca was low in almost all the soils. There was a positive correlation between K_F and exchangeable acidity (r = 0.87, p < 0.05) (Table 6) similar to findings by Hoseini and Taleshmikaiel (2013). This was because the soils were moderate in exchangeable acidity and at this soil pH, aluminium was very soluble in soil solution and should be responsible for phosphorus adsorption. Soil clay fraction also correlated positively with K_F (r = 0.67, p < 0.05) illustrating that soil texture played a major role in P adsorption of these soils. This was in conformity with the findings of Tening et al. (2013) who reported a net negative significant correlation between percent fixed P and available P and attributed P-fixation to the soil pH and clay content. Clay minerals are not only important in cation exchange reactions in acidic soils but they are perhaps a major factor governing the availability of phosphate in many soils. This could be the case with these soils given that the major clay minerals were kaolinite as judged from the activity index. Clay content had a negative and significant correlation with soil pH (r = - 0.90, p < 0.01) and positive correlation with exchangeable acidity (r = 0.80 p < 0.05) (Table 5). This implies that the study area could be made up of clays containing high exchangeable aluminium (Al^{3+}) and

hydrogen (H$^+$) ions as found in most acid soils (Muindi et al., 2015).

Conclusion

The results depicted that Freundlich adsorption model is precise in predicting P-fixation in the soils of the Eastern flank of Mount Cameroon. These soils have the ability to fix P with the amount fixed increasing with increasing supply of P. Phosphorus fixation was site specific and revealed that the soils can adsorb up to174.58 mgPkg^{-1}.

Apart from Ca, exchangeable acidity, organic matter, clay and pH that influenced P fixation; other soil properties such as CEC, moisture content, and exchangeable Na also contributed significantly.

The study identified a wide range in P adsorbed on the soils. There is therefore need for more intensive plant growth experiments to understand the role and interactions of soil properties on P availability for each site in the area before valid and concise fertilizer recommendations.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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REFERENCES

Agbenin JO, Tiessen H (1994). The effects of soil properties on differential phosphate sorption by semiarid soils from northern Brazil. Soil Sci. 157:36-45.

Ali W, Hussain M, Ali M, Mubushar M, Tabassam MAR, Mohsin M, Nasir HAA (2013). Evaluation of Freundlich and Langmuir isotherm for potassium adsorption henomena. Int. J. Agric. Crop Sci. 6(15):1048.

Anghiononi I, Baligar VC, Wright RJ (1996). Phosphate sorption isotherm characteristics andavailability parameters of Appalachian acidic soils. Soil Sci. Plant Anal. 27:2033-2048.

ASTM D-422-63 (1998). Standard Test Method for Particle-Size Analysis of Soils, ASTM International, West Conshohocken, PA.

ASTM D-4318-10 (2010). Standard test methods for liquid limit, plastic limit and plasticity index of soils. AST International Standards Worldwide, Pennsylvania.

Baskaran S, Bolan NS, Rahman A, Tillman RW, Macgregor AN (1994). Effect of drying of soils on the adsorption and leaching of phosphate and 2,4-dichlorophenoxyacetic acid. Austr. J. Res. 32:491-502.

Benedetti MF, Dia A, Riotte J, Chabaux F, Gerard M, Boulegue J, Fritz B, Chauvel C, Bulourde M, Deruelle B, Ildefonse P (2003). Chemical weathering of basaltic lava flows undergoing extreme climatic conditions: the water geochemistry record. Chem. Geol. 201:1-17.

Benton JJ (1999). Soil Analysis Handbook of Reference Methods. Soil and Plant Analysis Council. Inc Soil Sci. 2nd ed. CRC Press.

Bolan NS, Baskaran S (1996). Sorption and degradation of phosphate as influenced by soil depth. Austr. J. Soil Res.35:763-775.

Bolland MDA, Allen DG, Barrow NJ (2003). Sorption of phosphorus by soil. Government of Western Australia, Department of Agriculture. Bulletin 4591:1-30.

Brady NC, Weil RR (1996). The nature and properties of soils (11th ed.). Prentice Hall, New York.

Dhyan S, Chhonkar PK, Dwivedi BS (2005). Manual on soil, plant and water analysis. Westville Publishing House.

Gichangi EM, Mnkeni PNS, Muchaonyerwa P (2008). Phosphate sorption characteristics and external P requirements of selected South African soils. J. Agric. Res. Dev. Trop. Subtrop. 109(2):139-149.

Hadgu F, Gebrekidan H, Kibret K, Yitaferu B (2014). Study of Phosphorus adsorption and its relationship with soil properties, analyzed with Langmuir and Freundlich models. Agric. For. Fish. 3(1):40-51.

Harrison MR (2007). Principles of environmental chemistry. RSC Publishing, UK. P. 363.

Hazelton P, Murphy B (2007). Interpreting Soil Test Results: What do all the numbers mean? 2nd Ed. CSIRO Publishing.

Hoseini Y, Taleshmikaiel RD (2013). Comparison of phosphorus adsorption isotherms in soil and its relation to soil properties. Int. J. Agric. Res. Rev. 3(1):163-171.

Idris AOA, Ahmed HS (2012). Phosphorus sorption capacity as a guide for phosphorus availability. Afr. Crop Sci. J. 20:59-65.

Kim HT (1998). Principles of soil chemistry (3rd edn). Marcel Dekker, New York. P. 521.

Landon JR (1991). Booker tropical soil manual. A hand book for soil survey and agricultural land evaluation in the tropics and subtropics, pp. 1- 474.

Manga VE, Agyingi CM, Suh CE (2016). Trace element behavior in soils developed along the sopes of Mt. Cameroon, West Africa. Geochem. J. 50:267-280.

Manga VE, Suh CE, Agyingi CM, Shemang EM (2013). Mineralogy and geochemistry of soils developed along the slopes of Mt. Cameroon, West Africa. J. Afr. Earth Sci. 81:82-93.

Mehmood A, Akther MS, Hayat R, Memon M (2010). Phosphorus adsorption parameters in relation to soil characteristics. J. Chem. Soc. Pak. 32(2):129-139.

Melenya C, Logah V, Aryee D, Abubakari A, Tuffour HO, Yeboah IB (2015). Sorption of phosphorus in soils in the semi deciduous forest zone of Ghana. Appl. Res. J. 3:169-175.

Muindi EM, Mrema JP, Semu E, Mtakwa PW, Gachene CK, Njogu MK (2015). Phosphorus adsorption and its relation with soil properties in acid soils of Western Kenya. Int. J. Plants Soil Sci. 4(3):203-211.

Murphy J, Riley JP (1962). A modified single solution method for the determination of phosphates in natural waters. Anal. Chim. Acta 27:31-36.

Niang AI, Amadalo BA, De Wolf J, Gathumbi DM (2002). Specials screening for short term planted fallows in the highlands of Western Kenya. Agric. Syst. 56:145-154.

Olafur A (2008). Andosols. In Encyclopedia of Soil Science, Chesworth W (ed). Springer, pp. 1-44.

Page JB (1952). Role of physical properties of clays in soil science. Clay Technology in Soil Science. Univ. Wisconsin Press, Part IV. Bulletin 169:169-176.

Skempton AW (1969). The consolidation of clays by gravitational compaction. Q. J. Geol. Soc. 125(1-4):373-411.

Soubrand-Colin M, Neel C, Bril H, Grosbois C, Caner L (2007). Geochemical behavior of Ni, Cr, Cu,Zn and Pb in an Andosol-Cambisolclimosequence on basaltic rocks in the French Massif Central. Geodema 137:340-351.

Tan KH (1986). Degradation of soil minerals by organic acids. In Huang, PM and M Schnitzer (Eds): Interactions of Soil Minerals with Natural Organic sand Microbes. SSSA Special Publication 17, Soil Science Society of America, Inc., Madison, WI, pp. 1-27.

Tening AS, Foba-Tendo JS, Yakum-Ntaw SY, Tchuenteu F (2013). Phosphorus fixing capacity of a volcanic soil on the slope of Mount Cameroon. Agric. Biol. J. N. Am. 4(3):166-174.

Zehetner F, Miller WP, West LT (2003). Pedogenesis of volcanic ash soils in Andiean Ecuador. Soil Sci. Soc. Am. J. 67:1791-1809.

Zotarelli L, Dukes MD, Morgan KT (2010). Interpretation of soil moisture content to determine soil field capacity and avoid over-irrigating sandy soils using soil moisture sensors. University of Florida Cooperation Extension Services, AE460.