

Full Length Research Paper

Elucidating the causes of low phosphorus levels in ferralsols of Siaya County, Western Kenya

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Low available soil phosphorus (P) is one of the factors limiting crop production in western Kenya. Availability of soil P depends on amount of apatite, addition of P fertilizers, P fixing potential of a soil, soil water content and P removal by crops. Ferralsols are one of the major soil groups in Siaya County in western Kenya with low available P. We evaluated the possible causes of low available P in Ferralsols in the region. Composite soil samples (0-20 cm depth) were collected from various sites in Siaya County and analyzed for physical, chemical and mineralogical properties as well as P sorption characteristics to determine the cause(s) of low availability of P in these soils. The soils were weakly ($\text{pH}_{\text{water}} 6.02$) to moderately ($\text{pH}_{\text{water}} 5.06$) acidic and had aluminum (Al) saturation range of 1 to 69 g kg⁻¹. There were variations in the amounts of Al₂O₃, Fe₂O₃ and MnO ranging from 19.9 to 26.5%, 10.77 to 21.36% and 0.09 to 1.24%, respectively, in the soils. Boro, Malanga, Ndere, Wagwer, Ukwala and Yala soils had moderate organic carbon (OC) ranging from 1.48 to 2 g kg⁻¹, while Rangala, Sidindi, and Ugunja soils had low OC levels ranging between 0.5 and 1 g kg⁻¹. Phosphorus sorption by the soils increased with increasing amounts of P concentration in the medium. The P-sorption isotherms of the soils were characterized by two maxima. Oxides of Al and Fe together with clay and free Fe³⁺ and Al³⁺ were the main factors responsible for P-fixation in the studied soils. Phosphorus fixation in these soils should be reduced through liming and/or increasing organic matter content of the soils so as to increase P availability and thus crop productivity of the soils.

Key words: Clay, ferralsols, isotherm, phosphorus fixation, sesquioxides, soil profile.

INTRODUCTION

Maize is the staple food crop in Kenya (Woomer et al., 1998, 2001; Groote, 2002). Large farming areas are therefore dedicated to maize production. In western Kenya, maize crop yields are as low as below 500 kg of grain ha⁻¹ season⁻¹ compared to 6 to 8 t ha⁻¹ season⁻¹

produced under optimal agronomic conditions (Woomer et al., 1998; Okalebo et al., 2005). This situation threatens food security in the region. Declining soil fertility, particularly nitrogen (N) and phosphorous (P) has been identified as a major cause of low crop yields

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(Buresh et al., 1997). Phosphorus is an essential element for plant growth as it promotes respiration and photosynthesis. It occurs in the soil in the organic and inorganic forms and it is taken up from soil solution in the primary (H_2PO_4^-) and secondary (HPO_4^{2-}) orthophosphate ion forms. Phosphorus deficiency in soils presents a major constraint to world agricultural production (Palomo et al., 2006). In the eastern Africa region, low available soil P is a common occurrence in the highlands (Bekele and Hofney, 1993). The low available soil P has been widely recognized as one of the crucial and limiting factors to crop production in western Kenya (Sanchez and Palm, 1996; Buresh et al., 1997).

Availability of soil solution P depends on amount of apatite, addition of P fertilizers, soil P fixing capacity, soil moisture, P mineralization and P removal by crops. When P fertilizer is added to the soil, part of it goes to soil solution and is taken up by plants while the remaining is either adsorbed or precipitated (Sarraz et al. 2009), carried in runoff, leached or immobilized (Swift et al., 1994; Smaling et al., 1997). The high P fixing capacity of most tropical soils that makes a high proportion of inorganic phosphate unavailable to crops is a major cause of low P availability (Warren, 1992). Soluble soil P can be fixed by oxides, hydroxides and oxyhydroxides of Fe, Al and Mn, and also by clay minerals thereby reducing its availability to plants (Tsado et al., 2012). Other causes of low availability of P are low inherent soil P due to small amounts of apatite, the primary P-containing mineral (Nyandat, 1981; Mokwunye et al., 1986; Warren, 1992), continuous removal of P through crop harvests without sufficient replenishment (Stoorvogel et al., 1993), and erosion of top soil by run-off water (Swift et al., 1994; Smaling et al., 1997).

Ferralsols are one of the major soil groups in Siaya County in Western Kenya (Sombroek et al., 1982) with low available P (Njui and Musandu, 1999; Wasonga et al., 2008). There is lack of information on the specific cause(s) of the low availability of soil P in the Ferralsols of Siaya County in western Kenya. Knowledge of the cause(s) of low P availability is prerequisite in devising mitigation measures in order to enhance soil P nutrition and improved crop productivity. In this study, the possible cause(s) of low availability of P in the Ferralsols of Siaya County were evaluated.

MATERIALS AND METHODS

Study area

Siaya County is located in western Kenya, between latitude $0^{\circ}26'$ to $0^{\circ}18'N$ and longitude $33^{\circ}58'E$ and $34^{\circ}33'W$ at an altitude range of 1140 to 1500 m above sea level. It covers a surface area of approximately 2,530 km^2 with a population of 842,304 persons (Kenya National Bureau of Statistics, 2010). The region receives 1170 to 1450 mm per year of bimodal rainfall with temperature range of 15 to $30^{\circ}C$. The bimodal rainfall pattern allows for two cropping seasons of maize per year (Jaetzold and Schmidt, 1983).

The long rains occur from March to June while short rains are received between September and December. The most common soils in the study area are Ferralsols and Acrisols (Sombroek et al., 1982).

Soil sampling and sample preparation

Composite soil samples were collected by boring 0-20 cm depth of soil at random spots from 10 sites in Siaya County. The sites were Boro, Malanga, Ndere, Rangala, Siaya ATC, Sidindi, Ugunja, Ukwala, Wagwer and Yala (Table 1). Malanga, Rangala, Siaya ATC and Ukwala sites had previously been used as demonstration farms (*pers. com.*) while the rest were ordinary farmers' fields. At each site, the soil samples were collected from 15 random spots and mixed thoroughly in a plastic bucket to produce a composite sample. The composite samples were separately air dried on a flat top in a laboratory at room temperature ($20^{\circ}C$) for 4 days, cleaned of any evident plant residues and gravel, ground and passed through 2.0 mm sieve to obtain fine soil samples. Three sub samples were drawn from each of the composite samples and used for the various physical, chemical and mineralogical analyses.

Soil analysis

Soil textural class was determined by the hydrometer method (Bouyoucos, 1962) after dispersion with sodium hexametaphosphate. Laboratory procedures described by Okalebo et al. (2002) were used to determine soil pH, exchangeable acidity, total N, total P, available P and exchangeable bases. Soil pH was determined electrometrically both in distilled water and 1.0 N KCl in solution ratio of 1: 2.5 using a glass electrode pH meter (Model Hanna pH 11 microprocessor). Exchangeable acidity was determined by extracting the soil with 1 N KCl, followed by titration with 0.1 N NaOH. Total N and total P were determined by first digesting 0.3 g of soil samples with 2.5 ml of a mixture of H_2SO_4 - selenium (Se) mixture and salicylic acid on a block digester (Model JP Selecta) at $110^{\circ}C$ for 1 h, cooling the digest then adding 3 successive 1 ml portions of analytical grade hydrogen peroxide (to avoid phosphate interference) before raising the temperatures to $330^{\circ}C$ until the digest turned colourless. The digestive mixture was prepared by dissolving 3.5 g of Se in 1 L of concentrated H_2SO_4 and heating the mixture at $300^{\circ}C$ until its colour changed to clear light yellow, then dissolving 3.2 g of salicylic acid in 100 ml of the H_2SO_4 -Se mixture. The digested sample was cooled and made up to 50 ml with distilled water. To determine total N, the digest was diluted to a ratio of 1:9 (v/v) with distilled water. Five (5) ml each of reagents N 1 and N 2 (Okalebo et al., 2002) were successively added to 0.2 ml of the digest, each time vortexing for proper mixing. The mixture was allowed to develop colour for 2 h before measuring absorbance in UV spectrophotometer (Model T80 UV/VIS) set at 650 nm. In determining total P, 5 ml of the digested sample was pipetted in 50 ml volumetric flask, followed by addition of 20 ml distilled water and 10 ml ascorbic acid reducing agent (Okalebo et al., 2002) before making to mark with distilled water and shaking. Total P in the digest was determined in a UV spectrophotometer at 880 nm after colour development for 1 hour. Available P was extracted with Mehlich double acid method. The extracted P was determined by UV spectrophotometer set at 880 nm after colour development. To determine exchangeable bases (Ca^{2+} , Mg^{2+} , Na^+ and K^+), 5 g dry soil was leached with 100 ml of 1 M NH_4OAc (pH 7) to desorb the bases. The leachate was analyzed for exchangeable bases. Potassium and Na were determined using flame spectrometer (BUCK Scientific PFP-7), while calcium and magnesium were determined using atomic absorption spectrophotometer (S series Thermo Electron). Aluminum saturation (g kg^{-1}) was calculated as

Table 1. Some characteristics of the studied soils taken at 0-20cm depth.

Site	%Sand	%Silt	%Clay	Texture	pH (water)	pH (KCl)	Exch acidity (cmol/kg)	Exchangeable Al (cmol/kg)	Al saturation (g kg ⁻¹)	Organic C (g kg ⁻¹)	Total N (g kg ⁻¹)	Total P (g kg ⁻¹)	Available P (mg kg ⁻¹)	Ca (mg kg ⁻¹)	K (mg kg ⁻¹)	Mg (mg kg ⁻¹)	Na (mg kg ⁻¹)	Mn (mg kg ⁻¹)	Fe (mg kg ⁻¹)	Cu (mg kg ⁻¹)	Zn (mg kg ⁻¹)
Boro	38.6	50.6	10.8	SiL	5.61	4.20	0.19	0.05	2.4	2.00	0.30	0.13	19.34	1333	90	256	136	1.29	20.44	11.88	5.15
Malanga	45.8	26.0	28.2	SCL	5.78	4.25	0.10	0.01	1.1	1.66	0.59	0.17	24.39	1511	231	228	21	1.31	15.81	6.21	9.19
Ndere	60.5	12.7	26.8	SCL	5.36	3.87	0.56	0.36	14.2	1.63	0.39	0.14	11.86	669	66	208	81	1.09	16.17	6.46	3.69
Rangala	71.3	14.6	14.1	SCL	6.02	4.76	0.38	0.01	6.8	0.81	0.30	0.13	46.52	754	51	171	9	1.06	57.79	4.02	7.42
Siaya	46.1	20.6	33.4	SCL	5.13	4.07	0.28	0.15	5.5	1.17	0.45	0.15	28.07	966	90	271	21	1.51	28.19	6.99	4.99
Sidindi	76.5	14.6	8.8	SL	5.83	3.98	0.19	0.08	10.2	0.58	0.24	0.12	11.52	277	39	106	7	1.10	17.34	2.8	2.89
Ugunja	62.0	16.0	22.1	SCL	5.06	3.65	1.13	0.87	36.6	0.88	0.28	0.12	13.59	389	63	147	37	0.90	31.28	4.01	3.23
Ukwala	59.8	11.3	28.8	SCL	5.86	4.62	0.10	0.01	1.5	1.48	0.53	0.16	34.85	1112	51	193	28	0.82	26.34	5.27	10.23
Wagwer	57.8	16.7	25.5	SCL	5.12	3.58	2.85	1.89	68.7	1.70	0.64	0.12	16.63	309	55	51	14	1.59	31.95	3.75	2.99
Yala	53.8	22.7	23.5	SCL	5.53	3.76	0.95	0.66	17.8	1.74	0.59	0.13	16.41	1032	59	249	21	1.59	5.09	5.29	6.65
Cv%	4.6	8.6	12.2	nd	1.5	0.8	nd	nd	nd	4.5	4.0	0.6	4.1	5.9	7.1	4.1	12.5	3.9	10.0	3.5	4.6
Lsd _{0.05}	4.53	3.00	4.62	nd	0.16	0.02	nd	nd	nd	0.10	0.03	0.001	1.56	84	12	13	7	0.08	4.27	0.34	0.44

SiL, SL and SCL refer to silt loam, sandy loam and sandy clay loam respectively. nd = not determined because samples were not replicated.

$[(Al + H) / (K + Ca + Mg + Na + Al + H) \times 100]$ as outlined by Okalebo et al. (2002). The OC was determined colorimetrically following wet oxidation of OC with acidified dichromate (Allison, 1965).

Soil profiles and classification

Out of the initial ten sites that were sampled (Table 1), two sites (Ukwala and Ugunja) were later fenced off by private developers thus were not accessible for profile description and classification. The remaining eight sites were described and classified according to FAO (1988) soil classification system (Table 2). A profile pit was dug in each site. The observed horizons were demarcated, measured and described following FAO (2006) guidelines. In addition to on site profile description, soil samples were taken from each horizon and subjected to physical and

chemical analyses in the laboratory.

Mineralogical analysis of the studied soils

Out of the 8 described sites, Rangala and Malanga were Ferralic Cambisol and Rhodic Nitisol, respectively. Soils of the remaining sites were Ferralsols. Soil samples from these six Ferralsols sites were used for mineralogical analysis and P sorption study. Mineralogy analysis was done at the Department of Mines and Geology Laboratory using x-ray analysis.

Phosphorus sorption by the studied soils

Phosphorus sorption by the Ferralsols was determined by equilibrating the soil samples in 30 ml of 0.01 M CaCl₂

containing various amounts of P prepared from calcium tetrahydrogen diorthophosphate following procedure described by Fox and Kamprath (1970). Triplicate series of 2.5 g of 2 mm sieved soil sample was placed into 50 ml centrifuge tube followed by addition of 30 ml of 0.01 M CaCl₂ containing 0, 25, 50, 100, 200, 400, 800 and 1000 mg L⁻¹ P. Two drops of toluene (Fisher Scientific) were added into the suspensions to minimize microbial activity. A spatula scoop of activated charcoal (MERCK, Germany) was added to each suspension to improve filtrate clarity. The suspensions were shaken on a reciprocating shaker (SO₂) for a 30-minute period two times a day at 12 h time interval and left to equilibrate at room temperature of 20±2°C for 6 days. After six days (the time required for attainment of equilibrium), the samples were filtered through Whatman no.42 filter paper and 10 ml of the filtrate (including series of P standard solutions and reagent blanks of 0.01 M CaCl₂) were put in 50 ml volumetric

Table 2. Profile description of the sites.

Site	BORO			MALANGA			NDERE			RANGALA		SIAYA			SIDINDI			WAGWER			YALA		
Horizon	A _p	B _{ws}	B _v	A _p	B _{t1}	B _{t2}	A _p	AB	B _{ws}	A _p	B _w	A _p	B _{ws1}	BC _{ws2}	A _p	BA	B _w	A _p	B _{w1}	BC _{sq}	A _p	AB	B _{ws}
DEPTH (cm)	0-18	18-41	41-60	0-41	41-57	57-90	0-20	20-37	37-77	0-20	20-36	0-20	20-42	42-50	0-20	20-42	42-89	0-15	15-46	46-74	0-26	26-44	44-70
% sand	22	18	46	12	6	6	28	28	20	46	46	34	28	32	48	40	38	28	20	32	14	8	6
% silt	20	12	8	14	12	12	18	14	14	24	24	16	12	12	16	12	12	6	18	14	18	22	14
% clay	58	70	46	74	82	82	54	58	66	30	30	50	60	56	36	48	50	76	62	54	68	70	80
Texture	C	C	SC	C	C	C	C	C	C	SCL	SCL	C	C	C	SCL	C	C	C	C	C	C	C	C
pH (H ₂ O)	6.1	5.3	5.7	5.2	5.5	5.9	5.9	5.5	5.4	6.7	6.3	5.4	5.5	5.8	5.9	5.2	5.5	5.3	5.2	5.3	5.3	5.1	5.5
OC (g kg ⁻¹)	1.3	1.1	0.8	1.1	0.8	0.5	1.2	1	0.7	1	1	1.1	0.9	0.8	0.9	0.4	0.4	1	1	0.9	1.3	1.3	0.8
CEC (cmol(+)/kg ⁻¹)	14.6	11.4	9.0	9	7.0	7.8	6.6	7	5	7	5.4	5	4.6	5.4	5.0	5.8	5	4.6	5.4	8.2	5.4	7.4	8.6
Exch. Ca (mg kg ⁻¹)	1403	1213	1022	1312	1603	1493	1513	1243	932	732	902	952	722	1423	1202	1143	1132	621	634	702	1012	822	882
Exch. Mg (mg kg ⁻¹)	265	207	122	182	207	182	255	231	182	49	97	158	97	158	122	109	134	97	85	73	146	134	97
Exch. K (mg kg ⁻¹)	95	56	95	56	39	39	78	39	39	39	78	78	39	39	78	78	78	39	39	39	78	39	12
Exch. Na (mg kg ⁻¹)	23	23	23	23	23	23	7	7	7	7	23	23	2	23	23	23	23	7	2	2	23	23	7
Soil class	Plinthic ferralsol (FRp)			Rhodic nitisol (NTr)			Plinthic ferralsol (FRp)			Ferralic cambisol (CMo)		Plinthic ferralsol (FRp)			Xanthic ferralsol (FRx)			Plinthic ferralsol (FRp)			Plinthic ferralsol (FRp)		

C, SC and SCL refer to clay, sandy clay and sandy clay loam, respectively.

flasks. To each volumetric flask, 10 ml of freshly prepared ascorbic acid reducing agent (2.108 g ascorbic acid dissolved in 400 ml ammonium molybdate/antimony potassium tartrate solution) was added and the contents were mixed well and left to develop colour for 1 h. The concentration of P in the filtrate was read in spectrophotometer set at 880 nm. The difference in P concentration of the solution before and after shaking with soil was considered as adsorbed P. The adsorbed P was plotted against P concentration in the equilibrating solution to obtain P sorption isotherm.

RESULTS

Characteristics of the studied soils

There were significant differences (LSD_{0.05}) among the studied soils in their sand, clay and silt compositions (Table 1). Sand component

occupied the largest fraction of all the studied soils except Boro, with a range of 38.6 to 76.5% in the soil fraction. The clay and silt contents of the soils ranged from 8.8 to 33.4% and 11.3 to 50.6%, respectively. The soil texture of the sites ranged from silt loam (SiL) and sandy loam (SL) to sandy clay loam (SCL) (FAO, 1998). The soil acidity ranged from weakly (pH_{water} 6.02) to moderately acid (pH_{water} 5.06). Aluminum saturation (g kg⁻¹ dry soil) was very high at Wagwer (69 g kg⁻¹) and Ugunja (37g kg⁻¹), moderate at Ndere (14 g kg⁻¹), Sidindi (10 g kg⁻¹) and Yala (18 g kg⁻¹). The other sites had low Al saturation levels. Total nitrogen ranged from 0.24 to 0.64 g kg⁻¹ dry soil. Manganese (Mn) and iron (Fe) contents of the soils ranged from 1.59 to 0.82 and 57.79 to 5.09 mg kg⁻¹, respectively. There was significant difference (LSD_{0.05}) in amount of available P and

total P across the sites (Table 1). The available P was low in most of the sites, with only four sites (Malanga, Rangala, Siaya ATC and Ukwala) having adequate P (between 20 to 80 mg kg⁻¹ Mehlich extracted available P), below which available P is considered deficient (Hinga et al., 1980). Total P content of the sites was high ranging from 0.12 to 0.17 g kg⁻¹ dry soil. Basic cations, K, Ca, and Mg, contents of the soils ranged from 39 to 230, 309 to 1511, and 51 to 271 mg kg⁻¹, respectively (Table 1).

Soil profiles and classification

Profile description and soil classification of the sites are given in Table 2. While Rangala site had a sandy clay loam texture throughout the profile

Table 3. Mineralogical composition (%) of the studied soils (0-20cm depth).

Site	SiO ₂	Al ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	TiO ₂	MnO	Fe ₂ O ₃	Al ₂ O ₃ + MnO + Fe ₂ O ₃
Siaya	47.96	25.88	0.002	0.07	0.017	0.71	2.34	0.87	18.96	45.7
Yala	46.54	26.50	ND	0.12	0.075	0.47	2.78	0.50	10.77	37.8
Rangala	65.16	15.85	ND	0.11	0.160	1.47	0.23	0.09	14.77	30.7
Ndere	47.51	19.90	ND	0.06	ND	0.63	1.86	1.24	12.36	42.5
Wagwer	45.87	23.90	ND	0.10	0.118	0.74	1.93	0.49	21.36	36.8
Boro	46.05	24.46	0.017	0.06	0.040	0.61	3.54	0.52	19.86	44.8

ND = Not detected.

Table 4. Amount of P sorbed (mg kg⁻¹ soil) by the different soils at different concentrations of equilibrating solution.

Site	Equilibrating solution P concentration (mg L ⁻¹)								Mean (mg kg ⁻¹ dry soil)
	0	25	50	100	200	400	800	1000	
Boro	0	25	50	100	71.92	136.2	542.6	737.3	207.9
Ndere	0	25	50	100	116	138.4	535.5	738.3	212.9
Rangala	0	0	50	0	0	141.1	540.9	742.4	184.3
Siaya	0	25	50	100	78.1	137.7	537.7	733.5	207.8
Wagwer	0	25	50	100	182.9	137.7	535.2	731.3	220.3
Yala	0	25	50	100	149.5	143.4	541.8	742.8	219.1
Mean (mg kg ⁻¹)	0	20.8	50	83.3	99.7	139.1	539	737.6	-

LSD_{0.05} for the mean amount of sorbed P among the sites and among the equilibrating solutions are 16.96 and 150 mg kg⁻¹ dry soil, respectively.

horizons, the other sites were clayey in at least two horizons. All the sites were moderately acidic except Rangala which had a near neutral pH in the plough layer. Generally, the studied sites had low CEC and low basic cations down the profiles. The OC levels were low in the plough layer (0.5 to 1.3 g kg⁻¹) and decreased with increase in soil depth. Rangala and Malanga sites were classified as Cambisol and Nitisol, respectively while soils of the other eight sites were Ferralsols (FAO, 1988).

Mineralogy of the studied soils

The soils were silicate clays composed predominantly of oxides of silicon, Al, Fe and Mn (Table 3). All the Ferralsols had high Al₂O₃ and Fe₂O₃ ranging from 19.9 to 26.5% and 10.77 to 21.36%, respectively. Contrary, the MnO content was relatively low in all the soils ranging from 0.09 to 1.24%. The oxides of the basic cations were low in all sites.

Phosphorus sorption by the studied soils

The amount of P sorbed by the studied soils at different concentrations of equilibrating P solutions is summarised in Table 4. Generally, the amount of sorbed P increased

with increasing concentration of equilibrating solution. There were significant differences (LSD_{0.05}) for the mean sorbed P among the different equilibrating solution concentrations. Rangala soil sorbed significantly (LSD_{0.05}) lower amount of P than the other soils. Figure 1 shows that P sorption by the studied soils increased with increasing amounts of P concentration. All soils reached the 1st peak sorption level for P solution concentrations lower than 220 mg L⁻¹. The 1st maximum P sorption for Rangala, Boro, Siaya, Ndere, Yala and Wagwer soils were 50, 102, 103, 119, 150 and 180 mg kg⁻¹, respectively.

After attaining the 1st maximum P sorption capacity, the amount of P sorbed by soils was temporarily reduced, with Rangala soil recording slight P desorption between 90 and 200 mg L⁻¹ P concentrations. At P concentrations >400 mg L⁻¹, the soils regained linear and upward curves showing the increased sorption capacity above the 1st sorption maxima. But, the second sorption maxima of the studied soils were not reached.

DISCUSSION

Soil characteristics

Soils with low clay content are expected to have lower

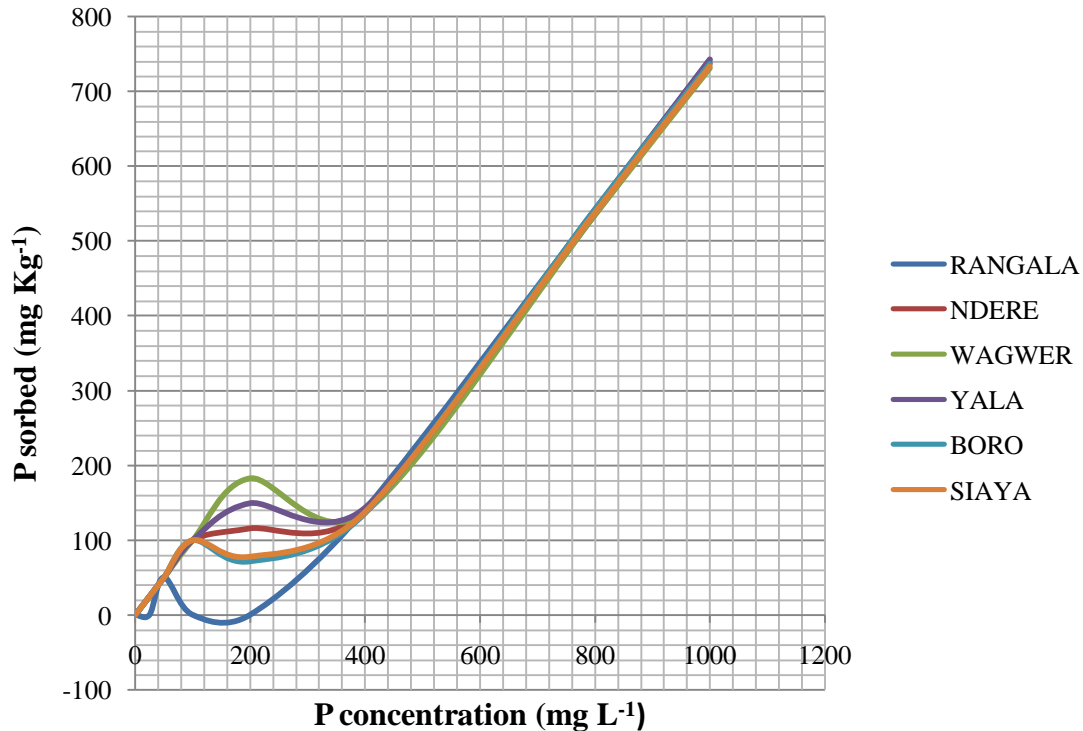


Figure 1. Phosphorus sorption (mg kg^{-1}) isotherms of the studied soils.

reactivity than soils with more content (Warren, 1992). Such soils were obtained from Sidindi, Boro and Rangala (Table 1). The blend of sand, clay and silt fractions in the 0-20 cm depth of soil from the various sites (Table 1) indicated a good aeration and water infiltration.

Total P content of a soil is contributed by the P-containing mineral – apatite, applied phosphatic fertilizers and organic matter content of the soil (Nyandat, 1981). The high total P contents of the soils in this study – ranging from 0.12 to 0.17 g kg^{-1} dry soil (Table 1) were likely to have been accumulating over the years. The soils of the region had been shown to be low in apatite (Nyandat, 1981), and majority of the farmers in the region are smallholders who rarely apply recommended rates of inorganic fertilizers (Okalebo et al., 2005; Ali-Olubandwa et al., 2011). Organic matter content of the soils were marginal to low (Table 1). It is likely, therefore, that a good proportion of the little phosphatic fertilizers applied to the farms and the inorganic P mineralized from organic matter were fixed by soil constituents over long period of time in order to build to high total P.

Mehlich-extracted P values of < 20, between 20 and 80, and > 80 mg kg^{-1} are considered deficient, adequate, and excessive, respectively (Hinga et al., 1980). Thus 6 out of 10 of the studied soils, Boro, Ndere, Sidindi, Ugunja, Wagwer, and Yala were deficient in available P (Table 1). Similar low available soil P had been reported in western Kenya (Njui and Musandu, 1999; Kisinyo et

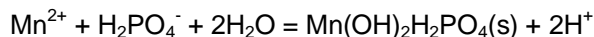
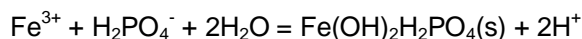
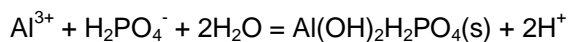
al., 2014). There were variations, however, depending on other factors such as previous management, farm history. The two sites, Rangala and Ukwala with adequate available P content (Table 1) were previously used as “Fertilizer Use” demonstration plots in the season preceding soil sampling period (*pers. com*). It may therefore be possible that these deficiencies can be overcome with inorganic fertilization.

Soils with Ca content >1000 mg kg^{-1} are considered deficient of the element (Okalebo et al., 2002). The majority of the sites (60%) had Ca contents lower than 1000 mg kg^{-1} (Table 1). Likewise, 90% of the sites had K content lower than 100 mg kg^{-1} (Table 1) which is also considered low to support plant growth (Okalebo et al., 2002). It is only Mg contents of the sites that were high (> 40 mg kg^{-1}) enough to support optimum plant growth (Okalebo et al., 2002), given other factors of production are not limiting. Thus, it may be assumed that low Ca and K contents in these soils constitute constraints for crop production, a situation that can limit crop response to P and other growth factors.

Phosphorus sorption

The mean amounts of P sorbed by the studied soils (Table 4) were similar to the amounts (107 to 294 mg P/kg) reported for other soils in the region (Kisinyo et al.,

2014). The high amounts of oxides of Al and Fe and low amounts of oxides of basic cations (Table 3) are indicative of weathered and leached soils where exchange sites are occupied by the acidic cations at the expense of leached bases (Kanyanjui et al., 2002). The significantly ($LSD_{0.05}$) lower sorbed P by Rangala soil than the other soils (Table 4) is attributed to low clay (Table 1) and low sesquioxides contents (Table 3) of Rangala site. Clay and sesquioxide contents of soils are important soil constituents responsible for fixing available P (Sarfaz et al., 2009; Amel and Ahmed, 2012). In the studied soils, P fixation was possibly affected by Al and Fe oxides since these oxides occurred in high amounts in these soils (Table 3). However, MnO occurred in low amounts and was not deemed to be a serious factor affecting P fixation capacity of the studied soils. Yala, Siaya, Boro and Wagwer soils had more Al_2O_3 than Fe_2O_3 , hence P fixation in these soils is possibly more due to Al_2O_3 than to Fe_2O_3 . Under acidic soil condition, P is removed from soil solution by Al, Fe and Mn to form solid precipitates as follows (Mahdi et al., 2011):



This can explain P fixation in the studied soils. Due to their exposed large specific surface areas, clay soils adsorb more P than other soil separates (Warren, 1992; Buresh et al., 1997). Thus, the types and amounts of P-fixing compounds vary with soils. In the studied soils, the Al and Fe oxides together with clay and free Fe^{3+} and Al^{3+} were considered the main factors for P-fixation.

Tsado et al. (2012) and Sarfaz et al. (2009) reported a significant but negative correlation between sorbed P and soil OC. The negative correlation between soil OC and P adsorption is explained by organic molecules released during organic matter decomposition complexing with Fe and Al ions, hence blocking the sites for P fixation. Therefore it may be necessary to increase the OC content of the soils of Siaya County to reduce the amount of P fixing ions in the soil.

The mean amounts of P sorbed by Siaya, Yala, Rangala, Ndere, Wagwer and Boro soils were 207.7, 219.1, 184.3, 212.9, 220.7 and 207.9 $mg\ kg^{-1}$ soil, respectively (Table 4). Rangala soil had the lowest content of sesquioxide (Table 3) which may explain the lowest P sorption, and sorbed low amounts of P. Incidentally, the rest of the soils had high amounts of sesquioxides and sorbed high amounts of P. This confirms that P sorption in these soils was largely due to sesquioxides. The low P sorption (and desorption between 90 and 200 $mg\ L^{-1}$ P concentration) by Rangala soil as opposed to the other soils was attributed to the soil's relatively high available P, high pH, and low clay

content, conditions which have been reported to reduce P sorption (Tsado et al., 2012; Kisinyo et al., 2014). Kisinyo et al. (2014) also reported similar P sorption capacities (107 to 294 $mg\ P\ kg^{-1}$) in western Kenya and attributed the P sorption to clay minerals like kaolinite, gibbsite, goethite, and Al and Fe oxides. Amel and Ahmed (2012) attributed P sorption in selected Sudanese soils to clay and iron content. The increase in amount of sorbed P with increasing P concentration (Figure 1) indicates the soils' potential to fix P with increasing P application rate. The P-sorption isotherms of the soils were characterized by two maxima (Figure 1). The 1st maxima were attained with P-concentration in the range of 60 and 260 $mg\ P\ L^{-1}$. The 2nd maxima were not realized indicating high potential of P fixation by these soils. Uzoho and Oti (2005) also reported the possibility of two sorption maxima in Nigerian soils. Two sorption maxima indicated existence of two different populations of adsorption sites with different affinities for P. The adsorption sites with higher affinity for P reached sorption maxima at lower equilibrating P solution concentrations (1st adsorption maximum) while those sites with lower affinity for P reached maxima at higher solution P concentration (2nd adsorption maximum). Increase in total negative potential at the surface due to sorbed phosphate and increased interaction between sorbed molecules was also proposed as possible explanation for the occurrence of the two adsorption maxima (Uzoho and Oti, 2005).

CONCLUSION AND RECOMMENDATIONS

The high amounts of sesquioxides, clay and free Fe^{3+} and Al^{3+} in Ferralsols of Siaya County are responsible for the high P-fixation, and consequently low availability of P in the soils. Increasing organic matter content of these soils could reduce the amount of P sorbed by the soils. In addition, liming these soils can improve P availability by reducing the concentration of the P fixing elements in the soils. In order to improve productivity of their fields, farmers should lime the soils, incorporate organic matter in the soils, and use phosphatic fertilizers. However, there is need for further research on the appropriate type and application rate of organic matter suitable for use in reducing P sorption in these soils.

Conflict of Interest

The authors have not declared any conflict of interest.

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