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Effect of Applied Lime and Mineral Phosphorus Fertilizer on Phosphorus Transformation in Acid Soils of West Wollega, Ethiopia

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ABSTRACT

Prevalent occurrence of P deficiency in strongly acid soils is one of the major problems limiting crop production in high rainfall regions of Ethiopia where Phosphorus (P) fixation, nutrient leaching and soils erosion are common. This work investigated effect of liming and applied mineral P on the P transformation of acid soils of West Wollega, Ethiopia. To study the P transformations, P fractionation was carried out to determine distributions of P in the various P pools. The soils were categorized as strongly acidic in which the pH (H_2O) values varied between 4.35 and 4.82. Cation exchange capacity (CEC) of the soils ranged from 20 to28 cmolc kg^{-}.^{1} Lime requirements to raise the soil pH to target values of 5.5, 6.5 and 7.2 varied from 4.27 to 8.18 tons $CaCO_3$ ha^{-1}. The total P contents of the studied soils ranged from 298.46 to 392.12 *mg kg^{-}.^{1} Available P(Bray I-P, Mehlich 3-P and $CaCl_2$-P) ranged from 1.12 to 1.82 mg kg^{-1} and considered as very low available P content. On average, distributions of applied P in the various fractions of the soils followed the order: iron bound P (Fe-P) > aluminum bound P (Al-P) > calcium bound P (Ca-P) > easily soluble P (ES-P) > reductant soluble P (RS-P). Clay content was highly positively correlated with total P, Fe-P, Ca-P, organic P and Bray I -P ($r = 0.86$, 0.76, 0.88, 0.89 and 62 respectively at $p < 0.01$ and $p < 0.05$). CEC was significantly correlated with total P, Fe-P, Ca-P, organic P ($r = 0.92$, 0.98, 0.89 and 0.78 respectively at $p < 0.001$ and $p < 0.01$). Desorption of P in the Fe-P and Al-P fractions were highly affected by the pH while desorption of P in the other fractions were modestly affected. The recovered mean percentages of the applied P were different among the soil types and P treatments ranging from 44.30% to 90.83%. This indicates that with proper lime treatment and optimum mineral P application, plant availability of P be increased in acid soils that highly fix applied P fertilizer.*

Key words: *P fractions, lime requirement, available P. P transformation, P recovery*

1. INTRODUCTION

Phosphorus (P) is one of essential macronutrients for plant growth and productivity. However, the plant available form of P in soil is low relative to those of other major macronutrients. This is because P, in the form of high valence phosphate (PO_4^{3-}), is strongly fixed by low solubility oxides of iron, aluminum and manganese or occluded into hydroxy-Al-interlayered montmorillonite clay particles. This transformation of inorganic P into unavailable forms is very severe in highly weathered acid soils in which iron, aluminum and manganese oxides are ubiquitous and the clay content is large (Jain, *et al.*, 2012). In highly weathered acid soils, even the momentary applied fertilizer P tends to become immediately and progressively less soluble over time (Eghball, *et al.,* 1996). This indicates that sufficient P application alone could not provide adequate P nutrient for healthy plant growth and maximum crop yield. In such highly weathered acid soils, acidic cations of Al, Fe, and Mn exist in high concentrations. These acid cations do not only aggravate soil acidity by displacing H^+ from solid soil particles, but also occupy large part of the available exchangeable sites of soil colloids, rendering the soil poor in exchanging the very essential nutrient cations such as Ca^{2+}, Mg^{2+} and K^+. Acid cations may occur as free cations in the soil solution, as exchangeable cations occupying exchangeable sites of soil colloids, or as mineral oxide clay-sized colloids with various levels of crystallinity. Applied or native P species significantly react with the acidic cations and become inactive (Brady and Weil, 2014). After sorption onto the acidic oxide surfaces, P will be only poorly desorbed. As time goes, P becomes more and more retained and unavailable (Martin, *et al.,* 2002).

The less productive crop growth in highly acidic soils in general and acid soils of Western Wollega in particular is related to P nutrient deficiency due to low native available form of P and high capacity of the soils to fix applied fertilizer P into strongly insoluble forms. Cultivation and other soil management activities bring significant differences in soil P chemistry in the area. Types of parent materials, degree of chemical weathering, soil ages, cultivation and fertilizer practices are among the major factors determining distribution of inorganic P forms in soils. (Achalu, *et al.* 2013; Sharpley and Smith, 1983).

Low-P availability problems in acidic soils can be alleviated by liming the soils for pH neutralization. Application of lime makes the carbonate (CO_3^{2-}) to be hydrolyzed and produce hydroxide ions (OH^-), which increase soil solution pH. The hydroxide ions react with Al oxides and reduce their positive surface charge. This in turn reduces the P retention capacity of the oxides (Mora *et al.* 1999). The increased concentration of OH^- ions in soil solution compete with P species (anions) for positive exchange sites on soil colloids. Thus liming reduces the ability of the acidic oxide surfaces to retain P in two ways: first reduces surface positive charge by pairing with the negative charges on OH^- ions; second by making the OH^- ions compete with PO_4^{3-} ions for the available positive sites on soil colloidal surfaces. The cumulative consequence is increased P availability (Kisinyo *et al*. 2014). Another method of alleviating P fixation problem is applying fertilizer P in excess quantity. This method temporarily addresses the low P availability but does not alleviate the root of the problem, that is, the acidic soil activity.

Soil P dynamics and its exchanges between the inorganic and organic pools highly affect its plant availability (Beck and Sanchez, 1994; Kpomblekou and Tabatabai, 1997). Several investigators reported effective use of P fractionation procedures or their modifications in estimating P forms associated with soil materials (Lopez-Pineiro and Garcia-Navaro, 2001). Fractionation procedure was developed based on the assumption that various extractants extract P selectively from discrete P pools. This approach is used to quantify the different chemical forms of P in soils (Hedley *et al*, 1982). The two dominant P reactions in soils are adsorption reaction at low P concentration and precipitation reaction at higher P concentration (Lin, *et al*, 1983; Mehadi and Taylor, 1988). The former is dominant over a short period while the later largely depends on the nature of cations in the soils. Several studies reported that there is correlation between the forms of inorganic P, status of available P, and transformation of inorganic fractions into fixed and occluded forms. This transformation depends on levels of added P, time of incubation and soil properties (Tekalign and Haque, 1991; Indiati, *et al*, 1992). The problem of low P availability and dynamics has been recognized and addressed in the past years, and there are several researches conducted in highly weathered soils in different parts of the world (Guedes *et al*. 2012; Tiecher *et al*. 2013; Asmare Melese, 2013). However, P dynamics in highly weathered acid soils of Western Wollega has not been studied. Thus, the aim of this work was to investigate the two methods of improving P availability, liming and P addition and to assess their effectiveness in relation to certain soil properties. It is also believed that high level of acidity and related soil properties largely affect general P dynamics of soils and its plant availability. Although there were studies made on soil P status and its adsorption/desorptions in some parts of Ethiopia (Tekalign and Haque, 1987; Duffera and Robarge, 1999; Achalu, *et al*, 2013), information on P adsorption-desorption properties of Western Wollega soils is lacking. To understand the prevalent occurrence of P deficiency in these soils, it is necessary to study the soil components that may be responsible for the distribution, availability, and P adsorption behavior of the soils. Therefore, this study investigated the change in the amounts and distribution of applied mineral P as affected by liming and the factors that might influence P adsorption and availability in four highly weathered acid soils of West Wollega, Ethiopia.

2. MATREIALS AND METHODS

2.1. Sites Description

Soil samples were collected from West Wollega Zone, Oromia region of Ethiopia, which is found at about 477 - 575 Km west of Addis Ababa. The districts selected for sample collection were Mana Sibu, Kiltu Kara, Nedjo and Boji Dirmaji. The altitude, the mean annual rainfall and the mean temperature of these areas range from 1300 to 1800 masl, 1000 to 2400 mmyr^{-1}, and 12.5 to 29 ^{0}C respectively. The areas receive rainfall in one season annually which lasts from April to October. The predominant soil type in southwest and western Ethiopia in general and the study area in particular is Nitisols according to FAO (2001) soil classification system. Its vernacular name is "*BiyeDima*" meaning red soil. Nitisols are deep and highly weathered, well drained, clay in texture and strongly acidic in reaction in the warm and humid areas of the west and southwest Ethiopia (FAO, 2001). The major crops grown in the zone include cereals (maize, teff, millet, sorghum, and barley), pulses (faba bean and field peas), oil crops (niger seed, rapeseed and sesame) and coffee.

2.2. Soil Sample Collection

Surface soil samples (0-20 cm) were randomly collected from each of the sampling sites in each district. The randomly collected soil samples were thoroughly mixed to form one composite sample for each site and a total of four composite soil samples were collected and packed in plastic bags. After bringing to HU soil laboratory, the collected samples were air-dried and ground to pass through a 2 mm sieve to be tested for selected soil physico-chemical parameters (bulk density, texture, pH, exchangeable acidity, organic carbon (OC), total nitrogen (TN), CEC, available P, exchangeable Mn, Al, and Fe) following standard laboratory procedures as described below. For greenhouse experiments, soils were collected from the same sites following the same procedures assuming 5 Kg soil for each pot experiment.

2.3. Physicochemical Analysis of the Soils

Selected physical and chemical properties of the soils were analyzed following their respective standard procedures. Particle-size distributions were measured by Bouyoucos hydrometer; organic matter was determined by wet oxidation; pH was measured before and after liming using a pH meter with combined-glass electrode in a 1:2.5 soil to solution suspension in deionized water. CEC of the soils was determined by ammonium acetate method. Organic carbon was determined by oxidizing with potassium dichromate in sulfuric acid solution and total nitrogen was investigated by the Kjeldahl procedure. Exchangeable acidity was measured by leaching hydrogen and aluminum ions from the soil by a neutral 1N potassium chloride and titrating the acidity brought into solution with standard solution of 0.02M NaOH (Van Reeuwijk, 1992). Al, Fe and Mn oxides were determined by extracting with ammonium oxalate measuring with atomic absorption spectroscopy, and electrical conductivity (EC) (1:1 H_2O) by following the methods according to Rowell (Van Reeuwijk, 1992). Available form of P was determined following Bray I (Bray and Kurtz, 1945), Mehlich 3-P (Mehlich, 1984) and $CaCl_2$ extraction methods.

2.4. Mineral Phosphorus Application, Liming and Incubation of the Soils

Lime requirements (LR) of the soils were determined to identify the correct quantity of lime to be added in each soil to obtain target pH values of 5.5, 6.5 and 7.2. In each of four bottles containing 10 g soil, an increasing volumes (0, 3, 6, and 9 mL) of 10 mM calcium hydroxide ($Ca(OH)_2$) solution was added. Then deionized H_2O was added to a total liquid volume of 25 mL, so that 1:2.5 w/v ratios of soil to solution were obtained. The bottles were shaken frequently for 7 days, and at the end of this equilibration period, the soil pH values were recorded. Next, mmolc $Ca(OH)_2$ g^{-1} soil that was used to achieve the target pH values was calculated, and this was extrapolated at field level (tones of equivalent $CaCO_3$ ha^{-1}) assuming a depth of incorporation of 30 cm and a bulk density of a value that was measured from core sample. After the liming test, 5 Kg soil samples were placed into pots and three levels of lime, as obtained from LR calculation for the three target pH values, were added to the soils in pots and thoroughly mixed and watered to field capacity. The treated soils were incubated for 56 days at room temperature. After 56 days of incubation, mineral phosphorus was added to the four soil samples as KH_2PO_4 in rates equivalent to 0, 50, 100, and 150 mg P kg^{-1} soil. Then the soils were mixed thoroughly and watered to field capacity. Control samples (without additions of P and lime) were included. Lime was analytical grade fine-sieved $CaCO_3$ powder. All the treatments and controls were in replicates. The resultant 128 pots (4 soils x 4 P levels x 4 lime levels x 2 replicates) were placed in an illuminated greenhouse for additional 56 days. Thus, the total incubation period was about 110 days, which corresponds to one cropping season. Finally, effects of the treatments and measured soil properties on phosphorus adsorbing capacities of the different P pools (fractions) were investigated by P fractionation method.

2.5. Phosphorus Fractionation

At the end of incubation period (110 days), the replicate samples of each P treatment were sampled, air-dried, ground for the subsequent P determinations. The fractionation procedures were based on the differential solubility of the various inorganic P forms in various extracts (Kuo, 1996). Ammonium chloride (NH_4Cl) was used first to extract easily soluble and loosely bound P (ES-P), followed by separating Al-P from Fe-P with ammonium fluoride (NH_4F), then extracting Fe-P with sodium hydroxide (NaOH). The reductant-soluble P (RS-P) was extracted with sodium citrate-sodium dithionite-sodium bicarbonate extraction (CDB). The Ca-P was extracted with sulfuric acid (H_2SO_4) since Ca-P is insoluble in CDB.

The extraction procedures were as follows: Three replicates of 1.0 g (<2 mm) of soil were added into a 100 mL centrifuge tubes. Then, 50 mL of 1*M* NH_4Cl was added to each tube and shaken for 30 min to extract the soluble and loosely bound P. The supernatant was centrifuged and decanted into a 50-mL volumetric flask and brought to volume with deionized water (extract A). Next, 50 mL of 0.5 *M* NH_4F (pH 8.2) was added to the residue and the suspension was shaken for 1 h to extract aluminum phosphates. Again, the supernatant was centrifuged and decanted into a 100-mL volumetric flask (extract B). Then, the soil sample was washed twice with 25-mL portions of saturated NaCl and centrifuged. The washings were combined with extract B and brought to volume with distilled and deionized water. Next, 50 mL of 0.1 *M* NaOH was added to the soil residue and shaken for 17 h to extract iron phosphate. Then, the supernatant solution was centrifuged and decanted into a 100-mL volumetric flask (Extract C). The soil was washed twice with 25-mL portions of saturated NaCl and centrifuged and the washings were combined with extract C and brought to volume distilled and deionized water. Next, 40 mL of 0.3 *M* $Na_3C_6H_5O_7$ and 5 mL of 1 *M* $NaHCO_3$ were added to the residue and the suspension was heated in a water bath at 85 °C. Then, 1.0 g of $Na_2S_2O_4$ (sodium dithionate) was added and the suspension was stirred rapidly to extract reductant soluble P. After continuously heated for 15 min, the suspension was centrifuged. Then, the supernatant solution was decanted into a 100-mL volumetric flask (extract D). The residual soil was washed twice with 25- mL portions of saturated NaCl and centrifuged. The washings were combined with extract D and diluted to volume. Then, extract D was exposed to air to oxidize $Na_2S_2O_4$. Finally, 50 mL of 0.25 *M* H_2SO_4 was added to the soil residue and shaken for 1 h. The suspension was centrifuged for 10 min and the supernatant was decanted into a 100-mL volumetric flask (extract E). Then, the residual soil was washed twice with 25-mL portions of saturated NaCl, and centrifuged. The washings were combined with the extract E and diluted to volume.

After five extracts were obtained for extraction of P from the different pools, an aliquot containing 2 to 40 μg P was taken from each of extracts A, B, C, D, and E into separate 50-mL volumetric flasks. Then, some deionized water and five drops of *p*-nitrophenol indicator were added to the volumetric flasks containing extracts C and E and the pH was adjusted with 2 *M* HCl or 2 *M* NaOH until the indicator color changed. To the volumetric flask containing extract B, 15 mL 0.8 *M* H_3BO_3 was added. Phosphorus concentrations in the various solutions (extracts A, B, C, D and E) were determined using the ascorbic acid method (Murphey and Riley, 1962) by preparing P standards that contain the same volume of extracting solution as in the extracts. Total P was determined by digestion with perchloric acid ($HClO_4$) as described by Sommers and Nelson (1972). Soil P availability indices were determined using Bray I, Mehlich 3, and $CaCl_2$ extraction methods. Using the determined values of P in the different extracts (pools), distribution of applied mineral phosphorus in the different P pools, effects of liming and applied P rates on desorbable phosphorus from the different P pools were investigated.

2.6. Statistical Data Analysis

For all of the measured parameters, two-way analysis of variance (ANOVA) was performed; one factor being lime and the other added P. The statistical difference between means was evaluated at the level of $P < 0.05$ with the least significant differences test. Correlation analyses between soil properties and the P extracted from the P pools as well as total P were done. For the statistical analysis, SAS statistical package was used.

3. RESULTS AND DISCUSSION

3.1. Selected Physicochemical Properties and lime requirements of the Acid Soils

The soil samples were collected from regions of high rainfall and highly weathered soils. Properties of the soils such as low pH, high levels of available aluminum, clay sized oxides and hydroxides of metals such as iron and aluminum, deep red to bright orange-red color, low exchangeable cations and organic matter, and reduced fertility makes them likely be classified under Oxisols according to the USDA classification system, though there is no information on soil classification in the area. All the soils were collected from cultivated lands.

Selected chemical and physical properties of the soils are given in Table 1. The soils were acidic with low pH values. Clay contents of the soils were medium. The soils had high CEC. The soil contained very low organic matter. The soils contained large amounts of exchangeable acidities. The oxalate extractable concentration ranges of acidic cations were 932 to 1134, 584 to 823, and 9.83 to 13.86 mg Kg^{-1} for Fe, Al and Mn respectively. The soil had very low available P form. This low available P could be due to high acidity and high P fixing cations of the soils. This is because the soils are highly weathered, typical acid soils with high concentrations of acidic cations aluminum, iron and manganese occurring either as free cations in the soil solution, as exchangeable cations occupying the best part of the available exchangeable sites of soil colloids, or as mineral oxide clay-sized colloids with various levels of crystallinity. Such acidic cations react with P species, dramatically reducing their activity (Brady and Weil 2014). Once sorbed onto oxide surfaces, P is capable of being only poorly desorbed, and P retention becomes progressively stronger with time (Martin, *et al.*, 2002). In addition, the soils showed significant differences in their P availabilities. This could be due to differences in their clay contents, cultivation and other soil management activities. This is in agreement with the work that reported that the distribution of inorganic P forms in soils reflect genetic differences, degree of chemical weathering, and fertilizer practices among soils (Sharpley and Smith 1983).

Table 1. Selected Physico-chemical properties of the soils

Soil Parameters	Soils			
	Boji Dirmaji	Nedjo	Kiltu Karra	Mene Sibu

(1:2.5 Soil/H_2O)	4.70	4.39	4.82	4.35
k density (g cm^{-3})	1.14	1.26	1.33	1.16
y (%)	55	48	46	45
C (cmolc Kg^{-1})	28	25	22	20
h. Ca^{2+}	2.41	3.53	2.14	2.44
h. Mg^{2+}	1.26	1.62	0.74	0.86
h. K^{+}	0.26	0.32	0.17	0.18
) (mg Kg^{-1})	976	1120	932	1134
) (mg Kg^{-1})	584	722	764	823
(O) (mg Kg^{-1})	9.83	13.34	14.18	13.86
h. acidity (cmolc Kg^{-1})	1.62	1.31	1.74	1.66
y I P (mg Kg^{-1})	1.82	1.45	1.12	1.64
hlich 3 P	6.12	3.48	4.32	8.64
Cl_2 P	0.03	0.04	0.12	0.13
otal) (mg Kg^{-1})	384.82	392.12	298.46	367.74
M (g Kg^{-1})	1.24	1.84	2.28	3.14

$Fe_{(O)}$, $Al_{(O)}$ and $Mn_{(O)}$ stands for 0.2*M* ammonium oxalate extractable Fe, Al, and Mn respectively, SOM = Soil organic matter, CEC = Cation exchange capacity

Lime requirement of the soils to raise the pH to target values of 5.5, 6.5 and 7.2 (Appendix Table 1) varied from 4.27 to 4.70; 5.38 to 6.44 and 6.98 to 8.18 tons $CaCO_3$ ha^{-1} respectively.

3.2. Transformations and Distributions of Applied P in the Different P Fractions

The forms and distribution of P in soils provide useful information in assessing P mode of transformations, status of available P and degree of chemical weathering in soils. The total P and plant available P indices of the treated soils were indicated in Appendix Table 2. For the four soils, distribution of applied P in different fractions is presented in Tables 2a, 2b, 2c and 2d. The extracted amounts of easily soluble P (ES-P), which are readily soluble and considered to be biologically available P (labile P) were much lower than those of residual P in all of the P and lime treated soils.

Table 2a. Effect of treatments on Phosphorus fractions, cumulative recovery and percent recovery of applied P in Boji Dirmaji soil

atment	P Fractions (mg Kg^{-1})						Cum.P	%P
	ES-P	Al-P	Fe- P	RS-P	Ca-P	Org.P	Recov	Recov
P_0L_0	0.73^{i}	5.01^{m}	13.6^{n}	0.07^{m}	0.12^{j}	0.83^{m}	C	C
P_0L_1	0.82^{i}	4.93^{m}	13.2^{o}	0.12^{m}	0.89^{h}	1.14^{l}	C	C
P_0L_2	1.19^{h}	9.71^{l}	13.95^{m}	0.37^{l}	0.38^{i}	1.92^{k}	C	C
P_0L_3	2.3^{g}	9.54^{l}	14.35^{l}	0.74^{k}	0.86^{h}	1.16^{l}	C	C
P_1L_0	3.21^{f}	17.42^{i}	14.44^{l}	1.01^{j}	1.64^{g}	2.14^{j}	19.50	39.00
P_1L_1	3.07^{f}	15.93^{j}	33.33^{j}	1.87^{i}	1.58^{g}	2.36^{i}	37.04	74.08
P_1L_2	3.16^{f}	22.58^{h}	35.86^{i}	3.11^{f}	2.64^{f}	3.78^{e}	43.61	87.22
P_1L_3	3.59^{e}	23.77^{g}	32.48^{k}	2.65^{g}	7.61^{b}	3.52^{f}	44.67	89.34

P_2L_0	4.82^b	15.65^k	47.02^h	2.25^h	5.51^c	2.42^h	57.31	57.31
P_2L_1	3.76^e	24.47^f	55.86^g	3.06^f	3.57^e	3.46^g	73.08	73.08
P_2L_2	4.39^c	36.84^e	66.08^d	4.29^d	7.65^b	4.75^c	96.48	96.48
P_2L_3	4.05^d	36.93^e	58.35^f	3.57^e	7.75^a	4.63^d	86.33	86.33
P_3L_0	4.74^b	39.38^d	59.82^e	7.99^a	5.51^c	3.44^g	100.52	67.01
P_3L_1	5.68^a	45.4^c	76.84^c	5.02^c	3.5^e	3.76^e	119.1	79.40
P_3L_2	4.77^b	50.29^a	98.6^a	6.85^b	7.78^a	6.92^a	147.69	98.46
P_3L_3	5.66^a	48.96^b	91.4^b	4.21^d	5.35^d	6.87^b	133.5	89.00
CV	3.90	0.577	0.299	3.42	1.53	0.800		
F- test	***	***	***	***	***	***		
R^2	0.994	0.999	0.999	0.998	0.999	0.999		

Means followed by the same letter within a column are not significantly different at $P > 0.001$; CV = coefficient of variation; *** = significantly different at $p < 0.001$; R^2 = correlation coefficient; C = P control sample; ES-P = easily soluble P; Al-P = Al bound P; Fe-P = Fe bound P; Ca-P = Ca bound P; RS-P = reductant soluble P; Org.-P = Organic P; P_0, P_1, P_2, and P_3 are P rates (kg P ha^{-1}) at 0, 52.77,105.51and 158.29; and L_0, L_1, L_2 and L_3 are lime rates (tons ha^{-1}) at 0, 4.27, 5.98 and 7.69. Means down the column with the same superscript letters are not significantly different. The means separating superscript letters work only down the columns.

Table 2b. Effect of treatments on Phosphorus fractions, cumulative recovery and percent recovery of applied P Nedjo soil

atment	P Fractions (mg Kg^{-1})						Cum.P	%P
	-P	P	P	-P	·P	g.P	Recov	Recov.
P_0L_0	0.18^l	5.28^m	7.76^m	0.42^o	0.8^n	1.24^l	C	C
P_0L_1	0.36^k	4.11^n	6.26^o	1.01^n	0.38^o	1.35^k	C	C
P_0L_2	0.67^j	6.92^l	13.93^l	1.74^m	1.33^m	2.13^j	C	C
P_0L_3	0.54^j	7.18^k	7.01^n	1.97^l	1.69^l	2.28^i	C	C
P_1L_0	1.45^i	17.79^h	16.86^j	4.15^j	3.18^k	2.14^j	29.89	59.78
P_1L_1	1.51^i	16.32^i	14.17^k	3.83^k	8.2^i	2.16^j	32.72	65.44
P_1L_2	3.59^g	17.92^h	27.61^i	4.42^i	13.43^e	3.22^g	43.47	86.94
P_1L_3	2.96^h	12.09^j	27.86^h	4.65^h	15.28^b	3.24^g	45.41	90.82
P_2L_0	4.89^f	20.05^g	37.91^g	8.88^g	12.82^c	3.46^f	72.33	72.33
P_2L_1	5.18^e	26.79^f	42.01^f	10.97^f	7.25^j	2.65^h	81.38	81.38
P_2L_2	7.92^c	32.98^e	48.06^e	13.06^c	14.82^c	4.78^c	94.9	94.90
P_2L_3	7.12^d	33.24^d	41.94^f	11.7^d	12.02^g	4.19^e	89.54	89.54
P_3L_0	7.89^c	33.29^d	53.58^d	12.52^d	10.28^h	4.54^d	106.42	70.95
P_3L_1	7.81^c	40.13^c	60.2^c	14.15^b	10.3^h	4.86^b	123.98	82.65
P_3L_2	9.89^a	55.24^a	82.43^b	15.02^a	18.15^a	5.62^a	159.63	106.42
P_3L_3	8.62^b	42.23^b	85.65^a	12.34^d	13.82^d	3.47^f	145.46	96.97
CV	2.30	0.399	0.331	1.634	1.072	0.854		
F- test	***	***	***	***	***	***		
R^2	0.999	0.999	0.999	0.999	0.999	0.999		

Means followed by the same letter within a column are not significantly different at $P > 0.001$; CV = coefficient of variation; *** = significantly different at $p < 0.001$; R^2 = correlation coefficient; C = P control sample; ES-P = easily soluble P; Al-P = Al bound P; Fe-P = Fe bound P; Ca-P = Ca bound P; RS-P = reductant soluble P; Org.-P = Organic P; P_0, P_1, P_2, and P_3 are P rates (kg P ha^{-1}) at 0, 52.77,105.51and 158.29; and L_0, L_1, L_2 and L_3 are lime rates (tons ha^{-1}) at 0, 4.34, 6.24 and 8.13. Means down the column with the same superscript letters are not significantly different. The means separating superscript letters work only down the columns.

Table 2c. Effect of treatments on Phosphorus fractions, cumulative recovery and percent recovery of applied P in Kiltu Karra soil

atment	P Fractions (mg Kg^{-1})						Cum.P	%P
	-P	P	P	-P	-P	g.P	Recov.	Recov.
P_0L_0	0.48^{l}	1.34^{p}	10.42^{o}	0.45^{l}	0.87^{l}	2.16^{n}	C	C
P_0L_1	0.25^{l}	2.34^{o}	13.42^{n}	0.76^{k}	0.73^{l}	2.42^{m}	C	C
P_0L_2	0.78^{k}	3.15^{n}	15.33^{m}	0.34^{l}	1.10^{k}	3.11^{l}	C	C
P_0L_3	1.19^{j}	3.78^{m}	16.57^{l}	0.86^{k}	1.48^{j}	3.28^{k}	C	C
P_1L_0	2.11^{i}	8.050^{l}	16.66^{l}	6.05^{i}	5.64^{g}	3.10^{l}	25.89	51.78
P_1L_1	2.94^{h}	12.43^{k}	25.46^{j}	5.61^{j}	5.38^{h}	3.48^{j}	35.38	70.76
P_1L_2	4.94^{g}	24.36^{i}	26.48^{i}	6.44^{h}	4.70^{i}	4.19^{i}	47.3	96.60
P_1L_3	4.96^{g}	20.67^{j}	24.53^{k}	7.76^{ef}	7.39^{d}	4.30^{h}	42.45	84.90
P_2L_0	8.27^{e}	27.56^{g}	30.00^{h}	7.89^{e}	8.76^{c}	4.45^{g}	71.21	71.21
P_2L_1	5.82^{f}	25.85^{h}	37.33^{g}	7.45^{g}	7.05^{e}	4.83^{f}	68.41	68.41
P_2L_2	8.38^{e}	37.22^{e}	57.73^{d}	7.54^{fg}	5.78^{g}	5.99^{c}	98.83	98.83
P_2L_3	10.05^{d}	30.31^{f}	51.24^{f}	7.89^{e}	11.19^{a}	5.92^{c}	89.44	89.44
P_3L_0	11.01^{c}	40.94^{c}	52.44^{e}	8.81^{c}	9.70^{b}	5.66^{e}	112.84	75.22
P_3L_1	10.88^{c}	47.16^{b}	68.48^{c}	8.29^{d}	6.75^{f}	5.82^{d}	127.46	84.97
P_3L_2	12.92^{a}	50.00^{a}	91.28^{a}	9.95^{b}	8.89^{c}	7.96^{a}	157.19	104.79
P_3L_3	12.53^{b}	39.80^{d}	84.08^{b}	10.52^{a}	11.23^{a}	7.26^{b}	138.26	92.17
CV	2.735	0.626	0.517	2.921	1.741	1.252		
F test	***	***	***	***	***	***		
R^2	0.999	0.999	0.999	0.998	0.999	0.999		

Means followed by the same letter within a column are not significantly different at $P > 0.001$; CV = coefficient of variation; *** = significantly different at $p < 0.001$; R^2 = correlation coefficient; C = P control sample; ES-P = easily soluble P; Al-P = Al bound P; Fe-P = Fe bound P; Ca-P = Ca bound P; RS-P = reductant soluble P; Org.-P = Organic P; P_0, P_1, P_2, and P_3 are P rates (kg P ha^{-1}) at 0, 52.77,105.51and 158.29; and L_0, L_1, L_2 and L_3 are lime rates (tons ha^{-1}) at 0, 4.46, 5.38 and 6.98. Means down the column with the same superscript letters are not significantly different. The means separating superscript letters work only down the columns.

Table 2d. Effect of treatments on Phosphorus fractions, cumulative recovery and percent recovery of applied P in Mene Sibu soil

atment	P Fractions (mg Kg^{-1})						Cum.P	%P
	-P	P	P	-P	-P	g.P	Recov	Recov
P_0L_0	0.46^{kl}	2.77^{n}	14.15^{m}	1.60^{k}	0.66^{l}	4.43^{i}	C	C
P_0L_1	0.56^{k}	2.42^{o}	13.3^{o}	1.39^{kl}	1.59^{k}	4.17^{j}	C	C
P_0L_2	0.24^{l}	3.01^{n}	13.94^{mn}	2.15^{j}	2.38^{j}	5.26^{h}	C	C
P_0L_3	0.64^{k}	3.36^{m}	14.70^{l}	2.36^{j}	2.88^{j}	5.28	C	C
P_1L_0	1.10^{j}	6.00^{l}	13.70^{n}	1.16^{l}	3.30^{i}	5.28^{h}	6.47	12.94
P_1L_1	1.78^{i}	12.52^{k}	16.32^{k}	2.32^{j}	4.43^{h}	5.88^{g}	19.82	39.64
P_1L_2	3.06^{g}	13.57^{j}	28.64^{i}	3.45^{i}	5.43^{f}	7.38^{d}	34.55	69.10
P_1L_3	2.82^{h}	14.8^{i}	22.75^{j}	4.60^{g}	4.95^{g}	7.06^{e}	27.76	55.52
P_2L_0	2.85^{gh}	16.24^{h}	47.85^{g}	4.24^{h}	4.76^{gh}	4.25^{ij}	56.12	56.12
P_2L_1	3.91^{f}	35.15^{g}	47.19^{h}	4.15^{h}	5.57^{ef}	4.32^{ij}	76.86	76.86

P_2L_2	4.50^{e}	40.21^{d}	68.27^{c}	8.84^{d}	8.80^{c}	6.49^{f}	110.13	110.13
P_2L_3	4.95^{d}	38.31^{f}	60.15^{e}	7.99^{f}	4.75^{gh}	6.90^{e}	93.83	93.83
P_3L_0	5.90^{c}	39.40^{e}	58.54^{f}	8.40^{e}	5.92^{e}	6.62^{f}	100.71	67.14
P_3L_1	6.53^{b}	56.94^{c}	65.48^{d}	9.28^{c}	6.50^{d}	8.12^{c}	129.42	86.28
P_3L_2	9.72^{a}	70.24^{a}	83.13^{a}	12.94^{a}	13.30^{a}	10.92^{b}	173.27	115.51
P_3L_3	6.53^{b}	61.50^{b}	70.72^{b}	10.5^{b}	9.35^{b}	12.19^{a}	141.57	94.38
CV	4.045	0.656	0.378	2.948	4.174	2.272		
F- test	***	***	***	***	***	***		
R^2	0.998	0.999	0.999	0.998	0.996	0.997		

Means followed by the same letter within a column are not significantly different at $P > 0.001$; CV = coefficient of variation; *** = significantly different at $p < 0.001$; R^2 = correlation coefficient; C = P control sample; ES-P = easily soluble P; Al-P = Al bound P; Fe-P = Fe bound P; Ca-P = Ca bound P; RS-P = reductant soluble P; Org.-P = Organic P; P_0, P_1, P_2, and P_3 are P rates (kg P ha^{-1}) at 0, 52.77,105.51and 158.29; and L_0, L_1, L_2 and L_3 are lime rates (tons ha^{-1}) at 0, 4.70, 6.44 and 8.18. Means down the column with the same superscript letters are not significantly different. The means separating superscript letters work only down the columns.

This indicates low P availability and infrequent as well as low P fertilizer application in these soils. The amounts of P extracted by sodium hydroxide (NaOH) and ammonium fluoride (NH_4F) were much greater than the other fractions of inorganic P. These inorganic P forms are iron oxide bound P (Fe-P) and aluminum oxide bound P (Al-P) forms respectively, and their occurrence in greater amounts evidences that the soils were highly weathered and rich in clay sized oxides. The relatively very large Fe-P fraction indicates that the soils contain high content of iron oxides that fix P. This is a common property of highly weathered acid soils of high rainfall regions (Verma, *et al.,* 2005; Tiecher, *et al.,* 2013). The lower RS-P fraction may be due to the fact that the soils contain large quantities of iron and aluminum oxides that the less soluble P forms exist in these fractions rather than in reductant soluble forms. On average, the P fraction in the four soils followed the order: Fe-P > Al-P > Ca-P > ES-P > RS-P. All these observations were also reported by several investigators (Dobermann, *et al.,* 2002; Zheng *et al.,* 2002; Zheng *et al.,* 2003; Verma *et al.,* 2005).

The correlations of P-fractions with the P taken up by plants were studied by several researchers and it was reported that the various P pools (fractions) are important source of available P in soils (Lopez-Pineiro and Garcia-Navaro, 2001). However, according to the present study, the various P fractions correlated with the P availability indices in large differences (Table 3.). The ES-P and Al-P fractions were highly significantly correlated to the three P availability indices and organic P significantly correlated to Bary I-P and Mehlich 3-P. However, the other P fractions did not correlate to the P availability indices except Fe-P with Mehlich 3-P which correlated significantly at $p < 0.01$.

Table 3. Linear correlation coefficients for availability indices and P forms

actions	P availability indices		
	Bray I –P	Mehlich 3-P	$CaCl_2$-P
al P ($HClO_4$)	NS	NS	NS
-P	0.91^{***}	0.96^{***}	0.82^{**}
P	0.94^{***}	0.86^{***}	0.84^{**}
P	NS	0.80^{**}	NS
-P	NS	NS	NS
-P	NS	NS	NS
.- P	0.79^{**}	0.76^{*}	NS

*'**' *** = Significant at $P < 0.05$, 0.01, 0.001 respectively and NS = not significant

ES-P = easily soluble P; Al-P = Al bound P; Fe-P = Fe bound P; Ca-P = Ca bound P; RS-P = reductant solubleP; Org.-P = Organic P

3.3. Effects of Selected Soil Properties on Extractable Phosphorus in the Different P Pools

The correlations between selected soil parameters and the P extracted from different pools are listed in Table 4. Clay content was highly correlated with total P, Fe-P, Ca-P, organic P and Bray I -P (R^2 = 0.86, 0.76, 0.88, 0.89 and 62 respectively at $p < 0.01$ and $p < 0.05$). This could be attributed to the properties of clay and clay-sized minerals that influence P adsorption and availability in acid soils. As the clay content increases, the proportions of P accumulating (adsorbing) soil components increases and as a result the desorbable total P increases. There was very strong correlation between CEC and several P fractions such as total P, Fe-P, Ca-P, organic P (R^2 = 0.92, 0.98, 0.89 and 0.78 respectively at $p < 0.001$ and $p < 0.01$). This is because soil colloids with high CEC adsorb phosphate ions strongly and in turn, the adsorbed phosphate ions alter the surface properties of colloids and impact the CEC. Exchangeable acidity also significantly correlated to Ca-P, organic P, BrayI-P and Mehlich 3-P (0.66, 0.72, 0.66 and 0.69 respectively at $p < 0.05$). This can be attributed to the fact that exchangeable acid cations of H^+ and/or Al^{3+} on the active sites of soil particle would exchange to relatively soluble cations such as K^+, Ca^{2+} etc, losing their adsorbed phosphate ions. As may be expected, pH was significantly correlated with a number of the P fractions. This is because many of soil reactions including P adsorption/desorption and surface properties of soils highly dependent on pH of the soils.

Table 4. Linear correlation coefficients for selected soil properties and P forms

		lay	C	Ↄ)	Ↄ)	(O)	acidity	M
al P	1^{*}	6^{**}	2^{***}				8^{**}	
-P			4^{*}					
P	7^{**}				8^{**}			

P	7^{**}	6^{**}	8^{***}	6^{**}				5^{*}
-P								
·P	6^{**}	8^{**}	9^{**}				6^{*}	4^{*}
ganic P		9^{**}	8^{**}				2^{*}	6^{**}
y I –P	4^{*}	2^{*}					6^{*}	
hlich 3-P	7^{*}		2^{*}	5^{*}			9^{*}	
Cl$_2$-P			2^{*}					

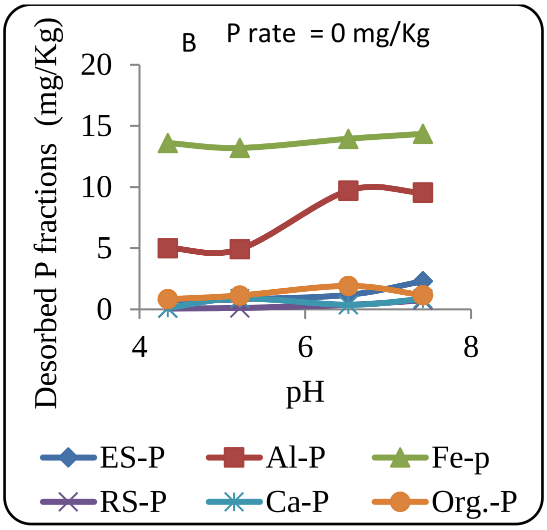
*,**, *** = Significant at $P < 0.05$, 0.01, 0.001 respectively; NS = not significant; ES-P = easily soluble P; Al-P = Al bound P; Fe-P = Fe bound P; Ca-P = Ca bound P; RS-P = reductant solubleP; Org.-P = Organic; SOM = soil organic matter, CEC = cation exchange capacity

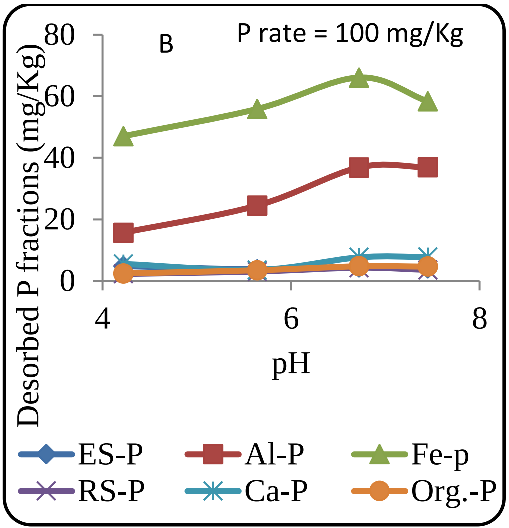
3.4. Effect of pH on Desorption of Applied P in the Different P Fractions

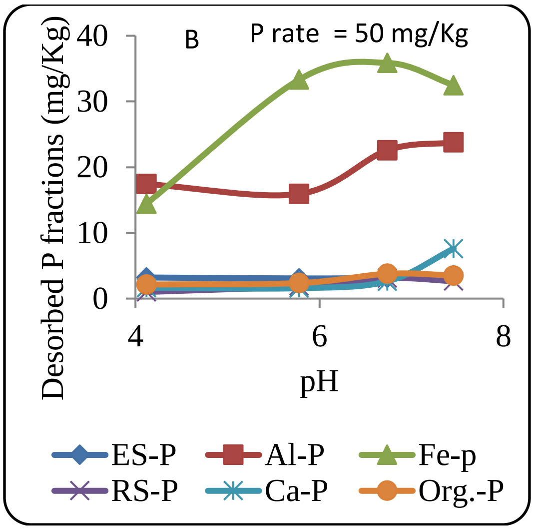
Desorptions of P in the various fractions (pools) were differently affected by the soil pH (Figure 1). The soil pH values were varied according to the lime and mineral P treatments. In general, desorption of P in the Fe-P and Al-P fractions were highly affected by the pH while desorption of P in the other fractions were modestly affected. This is because as pH of the soil increases the OH^- concentration increases and competes with P (PO_4^{3-}) for the positive sites on the Fe and Al oxide surfaces. Maximum P desorptions in the Fe-P fraction were observed at pH values of 7.25, 7.40, 7.25 and 7.27 for Boji Dirmaji, Nedjo, Kiltu Karra and Mene Sibu soils respectively. For the Al-P pool, maximum desorptions were obtained at pH values 7.25, 7,45, 7.25 and 7.27 and all were near to that of Fe-P fractions. Desorptions of P in the ES-P, RS-P, Ca-P and org.-P were slightly increased with pH and maximum desorption values were observed after pH value of 5.5.

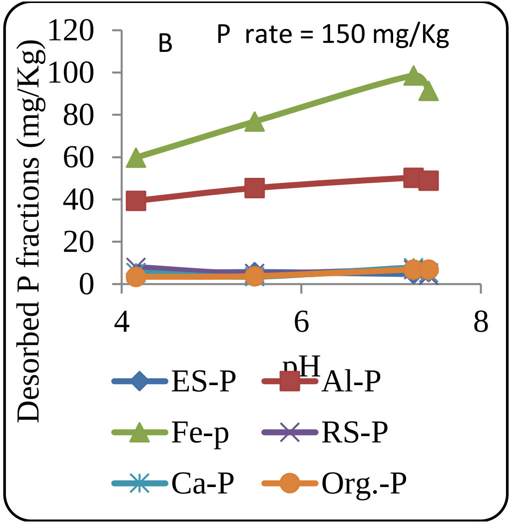
In general, at higher pH P (PO_4^{3-}) was more increasingly desorbed. This could be attributed to the effect of increased OH^- concentration that competes for positive sites on the surfaces of soil colloids and makes PO_4^{3-} ions less attracted. However, there was no uniform increment of P desorption. The maxima desorptions lied between about 5.5 to 7.25 depending on the sample backgrounds and level of treatments. However, at very high pH, P solubility began to decrease due to Ca-P mineral precipitation. This observation is in agreement with the results reported by Hartikainen and Simojoki (1997), Devau *et al*. (2011) and Weng *et al*. (2011). Researchers forwarded different reasons to explain the non uniformity of pH effects on P desorption. Harsh and Doner (1985) hypothesized based on their studies with P sorption onto hydroxy-Al-interlayered montmorillonite that increasing pH led to an increased stability of the hydroxy-Al interlayers and, therefore, to an increased P sorption and hence low P desorption. Hartikainen and Simojoki (1997) attributed the increased P solubility at low pH to the dissolution of Ca-P minerals such as apatite, which are known to exist also in acid soils

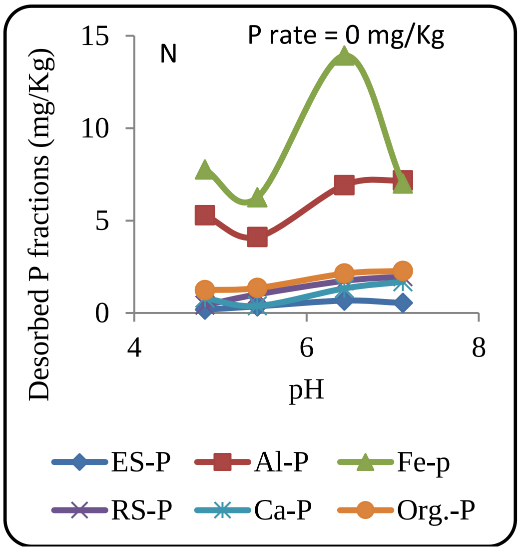
(Beauchemin *et al*., 2003). The sample background (pre treatments properties of the soils), applied mineral P rates and lime rates contributed to the varying P desorption maxima of the four soils. The larger the applied P rate, the higher the P desorption observed. This could be due to the fact that as the sorption sites on the soil colloids became saturated, P in the form of PO_4^{3-} became less adsorbed and stay in the solution form. This was observed in all of the four soils. The variation in P desorption among the soils types could be due to differences in clay mineralogy of the soils. The effect of liming rates depended on the rates of applied P. in relative term, desorptions of the residual P were less influenced by the liming and hence by the pH.

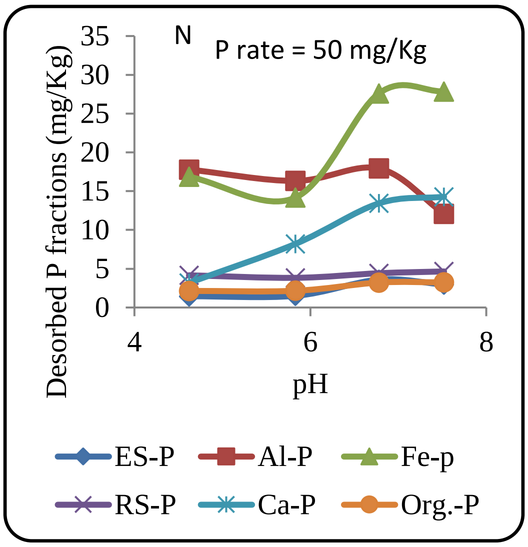









P rate = 0 mg/Kg
N
Desorbed P fractions (mg/Kg)
15
10
5
0
4
6
8
pH
ES-P
Al-P
Fe-p
RS-P
Ca-P
Org.-P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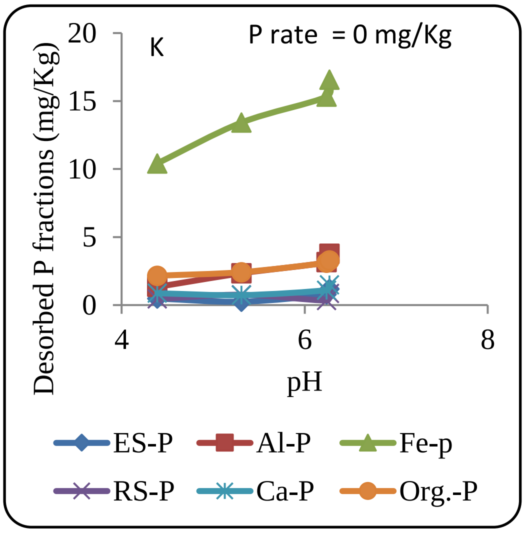
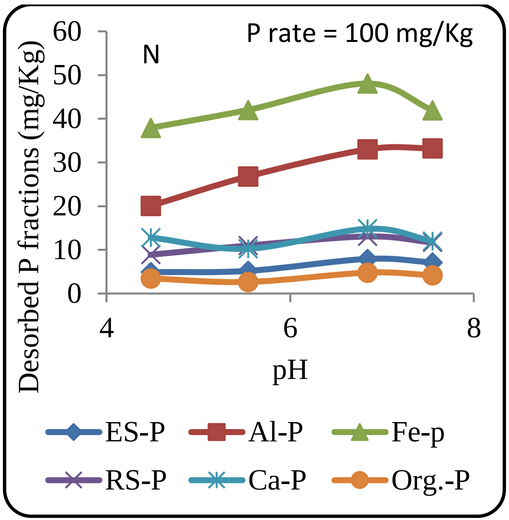
P rate = 50 mg/Kg
Desorbed P fractions (mg/Kg)
35
30
25
20
15
10
5
0
4
6
8
pH
ES-P
Al-P
Fe-p
RS-P
Ca-P
Org.-P


K
P rate = 0 mg/Kg
Desorbed P fractions (mg/Kg)
20
15
10
5
0
4
6
8
pH
ES-P
Al-P
Fe-p
RS-P
Ca-P
Org.-P


P rate = 100 mg/Kg
N
Desorbed P fractions (mg/Kg)
60
50
40
30
20
10
0
4
6
8
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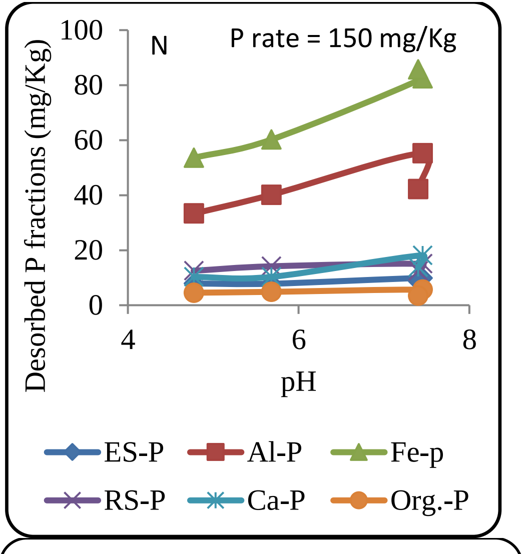
Fe-p
RS-P
Ca-P
Org.-P


N
P rate = 150 mg/Kg
Desorbed P fractions (mg/Kg)
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80
60
40
20
0
4
6
8
pH
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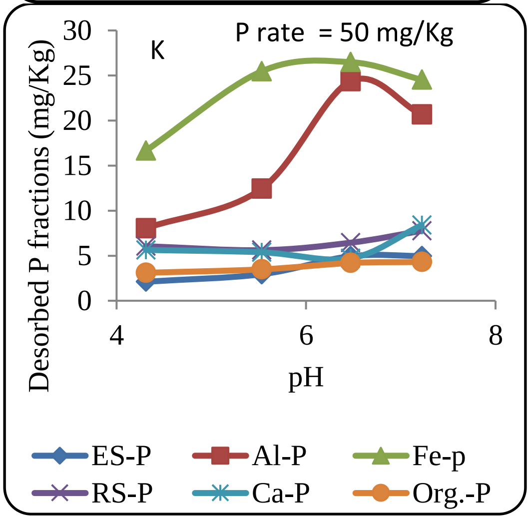
Fe-p
RS-P
Ca-P
Org.-P


K
P rate = 50 mg/Kg
Desorbed P fractions (mg/Kg)
30
25
20
15
10
5
0
4
6
8
pH
ES-P
Al-P
Fe-p
RS-P
Ca-P
Org.-P

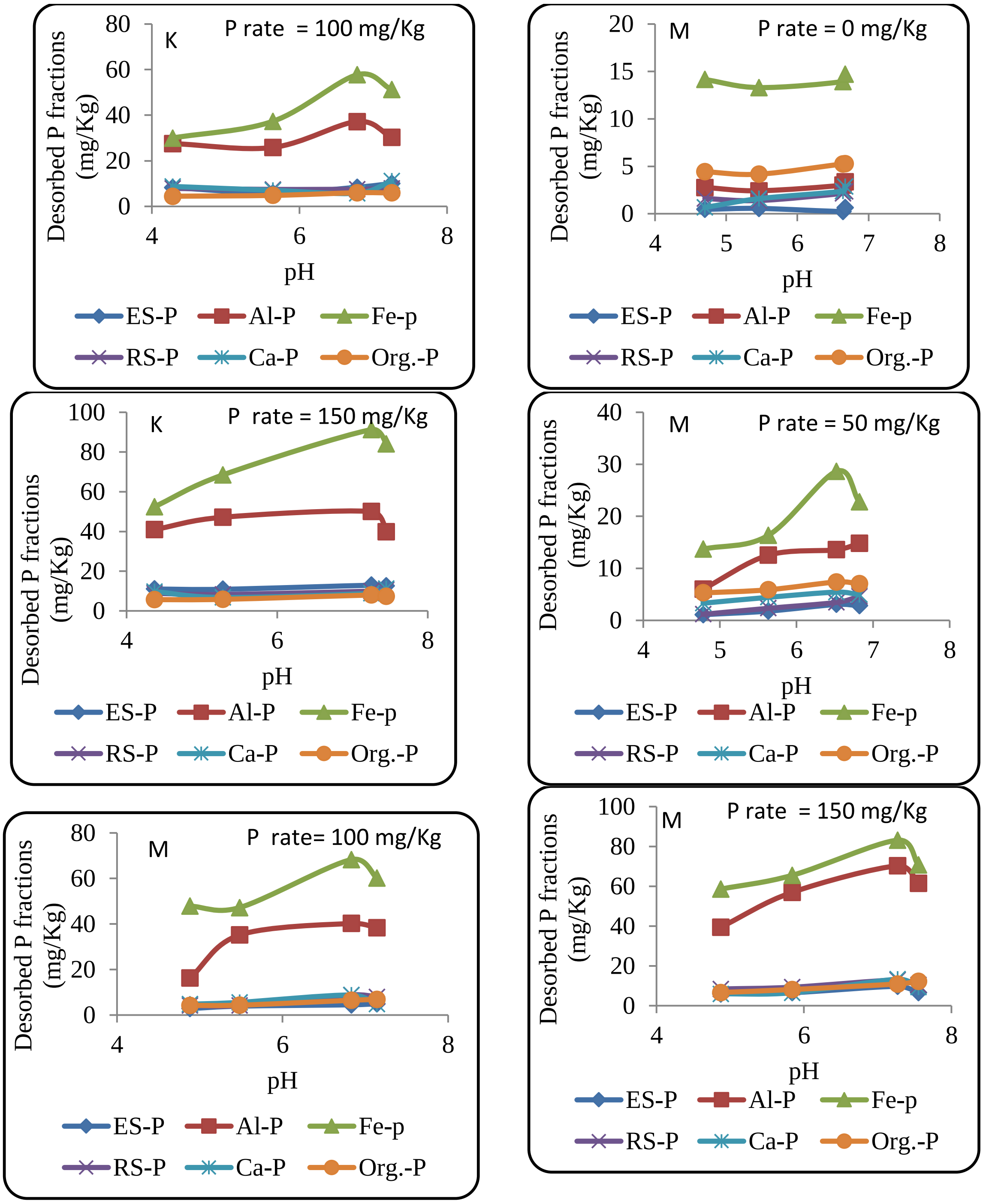


Figure 1. Effect of pH on desorbable P fractions at different applied P rate in the four soils B = Boji Dirmaji soil; N = Nedjo soils; K = Kiltu Karra soil; M = Mene Sibu soils; ES-P = easily soluble P; Al-P Aluminum bound P; Fe-P = Iron bound P; RS-P = Reductant soluble P; Ca-P = Calcium bound P; Org.-P = organic P

3.5. Effect of P Rates and Liming on Distributions of Applied P in the P Fractions

The effects of liming and applied P on the P fractions and total P recovery are presented in Table 5. The recovered mean percentage distributions of the applied P were significantly different among the sample types and P treatments. This could be attributed to three facts: first, these soils are acidic and elements such as aluminum, iron and manganese and clay sized sesquioxides are abundant adsorb P in different degrees; second, the different levels of P applications contribute different amounts of P to each P fractions; third, the extracting abilities of the different extractants lead to different amounts of extracted P.

Although the effect of lime treatment was low compared to P application, liming brought considerable effect on the cumulative amounts of P fractions recovered. This can be seen by comparing the amounts of P recovered from no lime and high level of lime treatments in which P level was constant. For example, the ES-P recovered from P_3L_0 ranges from 4.74 to 11.01 mg P Kg^{-1} while that recovered from P_3L_3 ranges from 5.66 to 12.53 mg P Kg^{-1}. This shows that by applying appropriate rate of lime only about 17% of the already existing P could be made plant available. In general, the distribution patterns of the P fractions in the four soils showed that ES-P in Kiltu Karra, Al-P and organic P in Mene Sibu, Fe-P in Boji Dirmaji and RS-P and Ca-P in Nedjo soils were the dominant fractions. This could be attributed to differences in clay mineralogy, P application and soils managements of the sampling areas. However, the level and patterns of organic P fractions of the four soils were relatively similar. This is because organic matter contents of all the soils were very low.

Table 5. Range of the total recovery of the added phosphorus

Soils	Recovery ranges	Applied P rates (mg Kg^{-1})		
		50	100	150
iDirmaji	Range (%)	39.00 – 89.34	57.31 – 96.48	67.01 – 98.46
	Mean (%)	72.41	78.30	83.47
Nedjo	Range (%)	59.78 – 90.82	72.33 – 94.90	70.95 – 106 - 42
	Mean (%)	75.75	84.54	89.25
Kiltu Karra	Range (%)	51.78 – 96.60	71.21 – 98.83	75.22 – 104.79
	Mean (%)	76.01	81.97	89.29
Mene Sibu	Range (%)	12.94 – 69.10	56.12 – 110.13	67.14 – 115.51
	Mean (%)	44.30	84.25	90.83

CONCLUSION

In this experiment, P fractionation was carried out after incubating the strongly acid soils to study effect of liming on applied P distribution among the P pools. The soils were strongly acidic and have low levels of available P. The levels of acidic cations of Al and Fe were very high, therefore, the soils adsorb and fix large portion of added P.

The results of this incubation experiment showed that applications of mineral P and lime significantly increased the amounts of P desorbed from all of the P fractions. It was observed that appropriate liming rates could make the unavailable, even strongly fixed soil P to become plant available. Therefore, applying sufficient amounts of mineral P alone is not enough in regions of strongly acidic soils with high P fixing capacity. Rather, applying good quality liming materials with appropriate rates is among the best management strategies for the sustainable use of the potentially productive but strongly acidic and highly weathered farmlands in the high rainfall regions of Ethiopia. This amendment of strongly acid soils by liming has dual benefits. First, it minimizes the cost required to apply large quantity of mineral fertilizer by reducing P fixation. Second, it reduces environmental pollution caused due to excess application of mineral P. The effects of clay mineralogy of the soils and the most appropriate timing of lime application in relation to fertilizer application and planting crops are all important additional factors to be investigated in further research.

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APPENDIX TABLES

Appendix Table 1. Lime Requirements (LR) of the four soils (tons $CaCO_3$ ha^{-1})

ls	pH of the soils	Target pH Values		
		5.5	6.5	7.2

	LR (tons CaCO$_3$ ha^{-1})			
i Dirmaji	4.38	4.27	5.98	7.69
djo	4.82	4.34	6.24	8.13
tu Karra	4.39	4.76	6.58	8.98
ne Sibu	4.70	4.70	6.44	8.18

Appendix Table 2. Total P and available P indices of the soils (mg Kg^{-1})

Treatments	----------------------Boji Dirmaji ------------ --------------				-------------------------Nedjo----------------- --------------			
	Total P	ray I P	Mehlich 3P	CaCl$_2$ P	Total P	ray I P	Mehlich 3P	CaCl$_2$ P
P_0L_0	384.82	1.82	3.12	0.03	392.12	1.45	3.48	0.04
P_0L_1	381.73	2.15	4.66	0.08	391.23	2.45	6.65	0.02
P_0L_2	384.66	2.51	9.41	0.19	394.61	3.53	8.73	0.13
P_0L_3	388.38	2.82	9.73	0.14	398.33	2.84	8.14	0.08
P_1L_0	396.78	2.15	5.32	0.14	398.71	2.23	8.22	0.11
P_1L_1	408.47	2.16	10.84	0.33	418.42	2.26	10.46	0.16
P_1L_2	421.77	2.46	13.16	0.58	428.71	2.46	14.46	0.24
P_1L_3	414.34	2.75	13.70	0.52	434.24	2.54	14.72	0.20
P_2L_0	410.83	1.58	7.18	0.42	445.88	1.46	10.46	0.16
P_2L_1	433.44	3.36	13.76	0.46	463.44	3.16	14.96	0.62
P_2L_2	461.23	4.55	15.25	0.72	481.93	4.22	16.52	0.78
P_2L_3	459.34	4.52	14.84	0.65	489.24	4.64	17.66	0.69
P_3L_0	470.48	2.75	9.25	0.44	517.38	2.96	10.92	0.54
P_3L_1	512.73	3.56	14.63	0.76	528.23	3.96	17.56	0.83
P_3L_2	531.65	7.38	18.48	0.92	541.52	7.88	19.84	1.22
P_3L_3	523.42	5.52	19.12	0.87	538.14	5.56	18.78	1.47

Appendix Table 2. (Continued)

reatments	----------------------Kiltu Karra-------------- -----------				-------------------------Mena Sibu------------ -------------			
	Total P	ray I P	Mehlich 3P	CaCl$_2$ P	Total P	ray I P	Mehlich 3P	aCl$_2$ P
P_0L_0	298.46	1.12	4.32	0.12	367.74	1.64	8.64	0.13
P_0L_1	290.83	2.85	4.85	0.12	361.43	2.25	8.29	0.10
P_0L_2	294.34	2.06	5.16	0.15	374.52	2.56	8.86	0.27
P_0L_3	296.63	2.82	5.84	0.18	382.48	2.82	12.12	0.28
P_1L_0	318.61	2.65	4.65	0.11	388.38	2.85	9.89	0.21
P_1L_1	318.42	2.16	5.16	0.18	400.17	2.66	12.66	0.28
P_1L_2	328.91	2.16	7.45	0.29	411.00	3.79	16.70	0.32
P_1L_3	334.84	2.24	7.24	0.30	415.94	3.24	14.94	0.36
P_2L_0	385.80	1.58	8.85	0.15	420.08	2.58	12.48	0.25
P_2L_1	363.73	3.37	9.27	0.82	437.34	3.36	17.32	1.32
P_2L_2	388.98	4.53	12.13	0.98	451.44	4.55	20.75	1.48
P_2L_3	399.14	4.52	10.82	0.90	462.54	4.52	17.52	1.92

P_3L_0	416.28	2.25	11.20	0.64	484.48	2.79	14.19	1.64
P_3L_1	428.63	4.56	14.16	0.82	509.23	3.56	20.76	2.22
P_3L_2	443.02	7.35	17.37	1.66	514.60	7.78	24.88	2.96
P_3L_3	438.17	5.56	15.96	1.89	513.92	5.57	22.97	2.89

P_0, P_1, P_2, and P_3 are P rates (mg/Kg) at 0, 50,100 and 150. L_0, L_1, L_2 and L_3 are lime rates (mg/Kg soil) at 0, 15.2, 30.4, and 45.6 for Boji Dirmaji; at 0, 14.5, 29.0, and 43.5 for Nedjo; 0, 13.5, 27.0, and 40.5 for Kiltu Karra and at 0, 18.5, 37, and 55.5 for Mene Sibu respectively.