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Inorganic Phosphorus Fractions Dynamics Following Phosphorus Application on Maize in Acid Soils

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Abstract: Soil properties influence phosphorus partitioning into functional pools and plant response to fertilizer application. A greenhouse experiment was conducted using three acid soils from southern Cameroon in order to i) have a better understanding of soil properties interactions with inputted P on maize performance and ii) assess changes in conceptual inorganic soil P pools . The soils which classified as Typic Kandiudox (TKO), Rhodic Kandiudult (RKU) and Typic Kandiudults (TKU) received 5 P rates ranging from 0 to 198.6 mg P pot^{-1}. Soil characterization revealed great differences in terms of physical soil properties and inorganic conceptual P pools. For all soils, $NaHCO_3$-Pi represented less than 2 % of total inorganic P (TIP) while NaOH-Pi and H_2SO_4-Pi pools emerged as the largest accounting for 13.2 and 85.1% of TIP, respectively. The observed P pools trend in the order HCl-Pi<$NaHCO_3$-Pi<NaOH-Pi <H_2SO_4-Pi confirmed the Walker and Syers model of P transformation over time. All soils were P-responsive with dry matter yield (DMY) increasing in the order TKU>RKU>TKO. Phosphorus fertilization induced differential increases in inorganic P pools with exponential models best explaining the dynamics of $NaHCO_3$-Pi pool with R^2 between 0.87 and 0.94. The HCl-P showed no consistent trend while NaOH-Pi and H_2SO_4-Pi as the most enriched pools followed linear models. Soil plant-system ordination through principal component analysis indicated that Ca and other basic cation levels influenced significantly P and N uptake and photosynthate allocation.

Key words: Acid soil · South Cameroon · Greenhouse · Inorganic P fractions · *Zea mays* L

INTRODUCTION

Ferralsols abound on stable landscapes of the humid tropics. These are inherently infertile soils with low levels available phosphorus (P), basic cations and nitrogen [1]. They are traditionally cropped using shifting cultivation techniques which make use of no fertilizers. In the perspective of stabilizing land use in these regions, strategies for enhancing soil fertility are needed. If nitrogen can be replenished biologically through symbiotic fixation, P availability depends on inherent soil condition imposed by parent material geochemistry, soil development stage and management practices. In recent years, with the economic development of the country, maize cultivation has gained importance evolving into commercially-oriented systems. Soil phosphorus chemistry is complex; its availability in most ecosystems depends on soil properties that regulate P availability, such as mineralogy of the parent material, soil texture [2]. In Cameroon, soil fertility is evaluated through traditional soil tests such as Bray 1 or Olsen P [3]. Phosphorus available to plants for uptake is perpetually in equilibrium with other P forms not measured by traditional soil P tests [4]. This highlights the necessity to measure these other sources known to contribute to plant P nutrition. Different sequential fractionation procedures have been developed that extract different forms of P in the soil [5,6]. These procedures assign differential liability to chemical P pools and have been used to investigate landscape pedological evolution [7], fate of P fertilizers in soils [8,4,9] and functional relationships among pools [10]. The main objectives of this study were to have a comprehensive understanding of soil properties interactions with inputted P on maize growth response to phosphorus and changes in P status using conceptual P pools of three acid soils from Southern Cameroon.

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MATERIALS AND METHODS

Greenhouse Experimentation: The soils used for the bioassay were collected from 3 sites in southern Cameroon: Minkoameyos (11° 25' 15" E, 3° 40' 05" N), Abang (11°31'34" E, 3°22'34" N) and Mengomo (11°00'45" E, 2°35'25" N). These sites are representative of a range of acid soils developed from Precambrian basement rocks and covering extensive areas in southern Cameroon and the whole Congo basin. They are respectively classified, at the subgroup level of the US soil taxonomy (Soil Survey Staff, 1994) as Rhodic Kandiudult (RKU), Typic Kandiudult (TKU) and Typic Kandiudox (TKO). These soils have a kaolinitic clay mineralogy with only traces of chlorites, quartz and interstratified minerals mainly in the TKU soils. A comprehensive description of these soils and their setting can be found elsewhere (21). In each of the 3 sites, surface horizon (0-10 cm) was collected in 4 fields under 1 to 2 years- C*hromolaena odorata* fallow. The greenhouse experiment was carried out at the International Institute for Tropical Agriculture, Yaoundé (Cameroon). Plastic pots were filed with 5 kg of sun-dried soil material crushed to pass a 4-mm sieve . Phosphorus was applied in the form of simple superphosphate at rates of 0, 33.09, 66.18, 132.36 and 198.54 mg P pot^{-1}. These rates corresponded to 0, 7.5, 15.0, 30.0 and 45.0 kg P ha^{-1} respectively. A basal application of 112 mg of K in the form of KCl and 280 mg N in the form of urea was applied in each pot to insure adequate supply of N and K. Six calibrated maize (*Zea mays* L. cv CMS 8704) seeds were sown initially and thinned to 4 plants 6 days after planting (DAP). Pots were arranged in a completely randomized block design with 4 replicates. The pots were brought to 60% field capacity daily by watering with deionized water. At harvest 42 DAP, shoots were cut off at the soil surface and weighed. The roots were hand-sorted from the soil, washed with water on a 2-mm sieve. Root and shoot weights were determined after drying in the oven at 65°C for 3 days. Soils from pots were removed, air-dried and sampled for P sequential fractionation analyses.

Laboratory Analyses: All routine physico-chemical analyses were carried out on air-dried soil samples ground to pass a 2-mm sieve following conventional methods. Oxalate-extractable Fe was determined according to Schwertmann [11]. Labile P was measured following the Bray-1 P method (0.03 M NH_4F and 0.1 M HCl) and P sorption according to Blakemore *et al.* [12]. Phosphorus and N contents in shoot and root maize samples were determined following [13]. A simplified four-step sequential extraction procedure adapted from [6] was used to evaluate the soil P status before and after pot experimentation. About 1g of soil was weighed in a 50-ml centrifuge tube and 30 ml of successive extractions were added. The tubes were shaken overnight for 16 hours with the successive extracting solutions (i) 0.5 M $NaHCO_3$ at pH 8.5 [14], (ii) 0.1 M NaOH, (iii) 0.5 M HCl and finally with 2 M H_2SO_4 after ignition at 550°C. At each step of the sequential extraction procedure, centrifugation was carried out at 3000 rpm for 15 min. Total inorganic P was calculated as the sum of P forms measured sequentially. All phosphorus analyses were done using the molybdenum blue method [1].

Data Processing and Statistical Analyses: Phosphorus uptake in shoot and accumulation in roots (PAR) were calculated as the product of P concentration times shoot or root biomass dry matter yield (DMY). Phosphorus uptake efficiency (PUE) was defined as the average change in shoots DMY obtained per unit of change in P input. One way analysis of variance was used to assess what soil properties and inorganic P pool varied across soil types. In case of statistical significance ($P<0.05$), means were separated using the DIFF option of the LSMEANS statement. A two-way analysis of variance (ANOVA) was also used to evaluate P rate and soil type effects on soil P fraction dynamics, maize growth and P uptake assessment variables. The predicted maximum attainable DMY was obtained by taking the first derivative of the DMY as expressed by the quadratic polynomial models set at P rate = 0. In order to explore the complex interactions between soil properties, P rate and plant growth parameters, principal component analysis (PCA) was used. Naturally, some degree of correlation were found between soil and plant growth variables used but they were maintained in a redundant model in order to capture hidden aspects of soil-plant system functioning. Component retention was based on the criteria of eigen value more than 1 and intuitive interpretation made taking into consideration underlying variables with loading absolute value more than 0.40. Regression and stepwise regression analyses were used to fine-tune relationships highlighted by PCA and determine which soil variables and/or P pools optimise DMY and P uptake estimations. All statistical analyses were performed using SAS statistical package [15].

RESULTS

Inherent Soil Properties and Native Inorganic Fractions: The one-way ANOVA indicated that the studied soils contrasted by most of their properties (Table 1). The TKO soils had significantly higher clay content, lower level of exchangeable Ca, Mg and K, higher level of P sorption and exchangeable Al. The TKU soils have relatively higher amounts of sand and silt. The RKU soils have higher soil reaction and amorphous iron. The trends in inorganic P pools were similar across the investigated with the greater proportion P being found in the residual and NaOH-P extractable pools. The $NaHCO_3$-P pool considered as plant available was significantly higher in RKU while higher values of NaOH-P and residual P were found in the TKO.

Soil Properties and Inorganic P Relationships to Maize Growth: Shoot and root DMY differed significantly across soil type and P rate. The interaction term was however not significant (Fig. 1). Shoot DMY trends as a function of P rate were best explained by quadratic polynomial models with coefficients of determination between 66.6 and 89.7%. The highest shoot DMY was observed in TKU with a control value of 11.4 g pot^{-1}. The lowest value was observed in TKO with a control DM of 6.8 g pot^{-1}.

Table 1: Mean ± S.E of selected properties and inorganic P fractions of the studied soilsof the soil used.

Soil properties$^{\delta}$	TKO	RKU	TKU
Sand (%)	40.8 ± 5.3^{c}	50.6 ± 1.6^{b}	52.8 ±3.0^{a}
Silt (%)	10.2 ± 1.8^{b}	9.70 ± 0.9^{b}	12.4 ± 0.9^{a}
Clay (%)	48.9 ± 7.1^{a}	39.7 ± 1.2^{a}	34.8 ± 3.8^{b}
pH water	4.5 ± 0.1^{c}	5.4 ± 0.1^{a}	5.1 ± 0.2^{b}
OC (g kg^{-1})	22.5 ± 1.9^{a}	16.1 ± 1.1^{c}	19.1 ± 1.1^{b}
TN (g kg^{-1})	2.1 ± 0.1^{a}	1.6 ± 0.1^{b}	2.0 ± 0.1^{a}
Ca (cmol(+) kg^{-1})	1.10 ± 0.10^{c}	1.35 ± 0.17^{b}	2.9 ± 0.40^{a}
Mg (cmol(+) kg^{-1})	0.33 ± 0.01^{b}	0.64 ± 0.06^{a}	0.7 ± 0.03^{a}
K (cmol(+) kg^{-1})	0.08 ± 0.01^{b}	0.06 ± 0.04^{b}	0.14±0.01^{a}
Al (cmol(+) kg^{-1})	0.63 ± 0.13^{a}	0.12 ± 0.02^{b}	0.16±0.07^{b}
P sorption (%)	88.3 ± 3.2^{a}	77.5 ± 0.3^{b}	67.7 ± 5.6^{c}
FeOx (%)	0.69 ± 0.04^{c}	2.30 ± 0.07^{a}	0.86±0.05^{b}
$NaHCO_3$-Pi	1.7 ± 0.3^{b}	3.2 ± 0.5^{a}	1.1 ± 0.3^{b}
NaOH-Pi (mg kg^{-1})	25.4 ±3.2^{a}	29.2 ± 1.2^{a}	13.1 ± 3.8^{b}
HCl-P (mg kg^{-1})	1.0 ± 0.5^{a}	0.86 ± 0.38^{a}	0.8 ± 0.2^{a}
Residual P (mg kg^{-1})	154.1 ± 2.3^{a}	190.9 ± 12.0^{a}	91.9 ± 3.8^{b}

$^{\delta}$For each property, values along the same row not followed by the same letter are statistically different at P<0.05.

Predicted maximum attainable DMY was significantly lower in TKO (26.2 g pot^{-1}) compared to 35.6 and 36.7 g pot^{-1} for RKU and TKU, respectively. Phosphorus rate and soil type have significant impacted on root/shoot

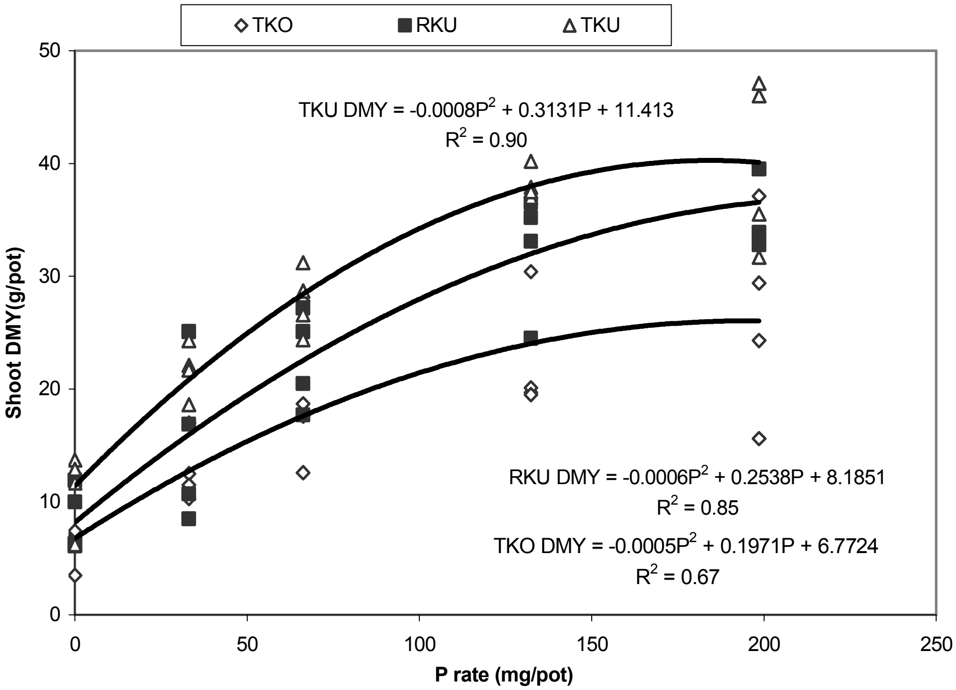

Fig. 1: Dry matter yield response as related to applied P rate. Observed (symbols) and fitted regression models

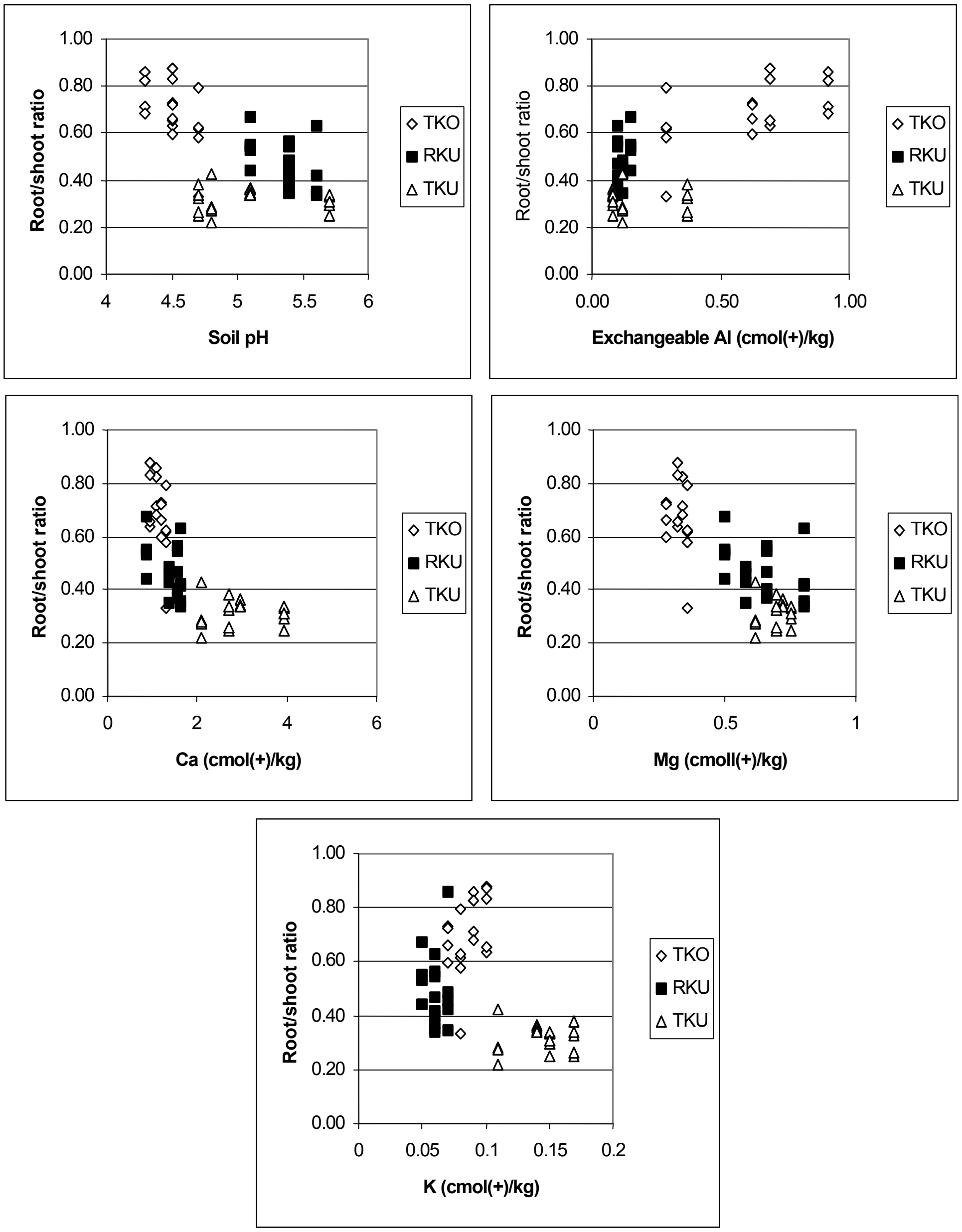

Fig. 2: Scatter diagrams showing the variation in root/shoot ratio as a function of pH, exchangeable Al and exchangeable bases

ratio with 88.1% of the variance being accounted for by soil type. Root/shoot ratio was related to several soil properties. Those that were negatively correlated with the root/shoot ratio were soil pH, exchangeable Ca, Mg and K (Fig. 2).

Fertilization Effects on P Pools: Phosphorus fertilization improved the soil P status with significant differences across conceptual inorganic P pools. All pools were increased with increasing P rate except for the HCl Pool which yielded no consistent trend. (Fig. 3). Exponential models best explained the dynamics of $NaHCO_3$-Pi pool with R^2 between 0.87 and 0.94. The HCl-P fraction seemed to peak following the second and third rate of P input. Using curvilinear models accounted for 76.8 % of variation in HCl-P in TKO and only 38.8 and 24.0 for TKU and RKU, respectively. NaOH-Pi and residual P increased linearly with increasing P rate One-way ANOVA results in control pots which received no P fertilizer pointed at differential changes in inorganic P fractions across soil

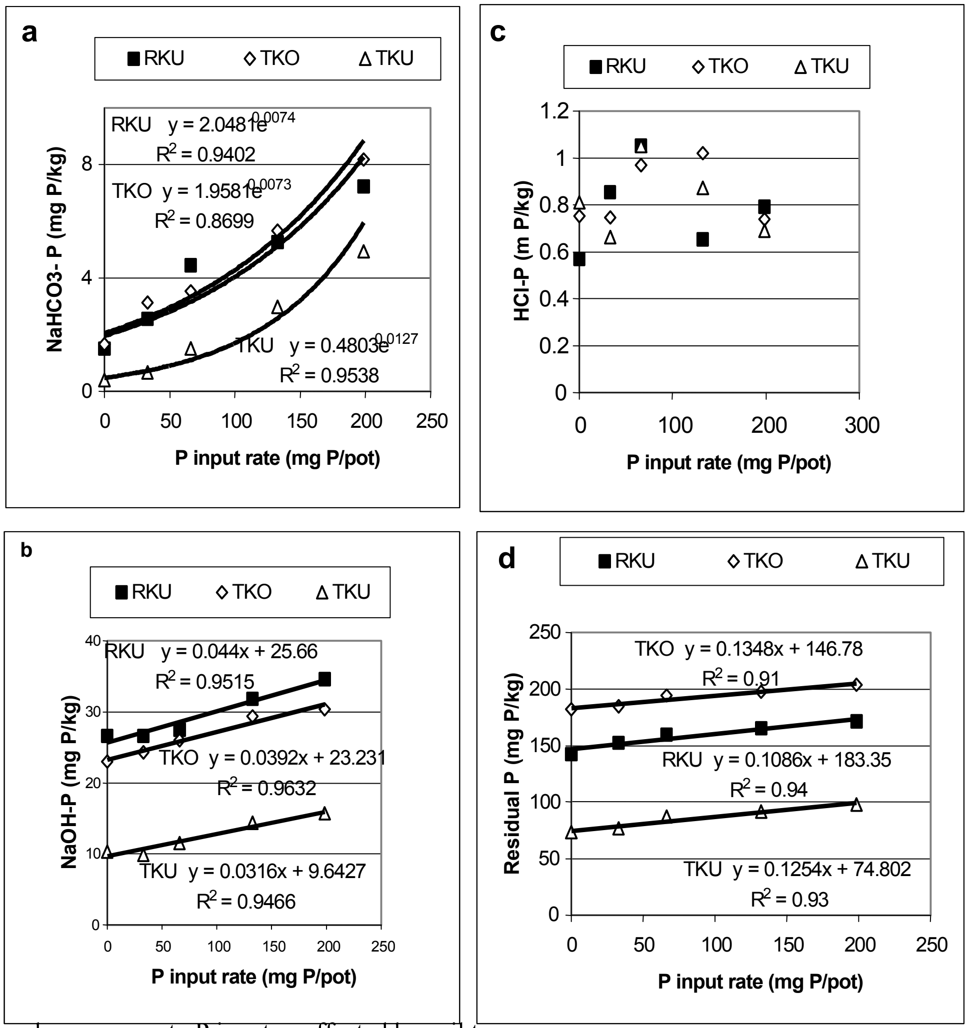

Fig. 3: Soil P pool responses to P input as affected by soil types

types (Fig. 4). The greatest variations in NaHCO$_3$-Pi pool were observed in RKU and TKU with 47 and 90%, respectively. In TKU soils, the NaHCO$_3$-Pi pool was significantly depleted, giving values close to detection limits by traditional colorimetric determination procedures.

Principal Component Analysis of the Soil-maize System: Principal component analysis of the soil-maize system was based on the complete data set model and yielded 5-components which accounted for 88.2% of total system variance (TSV) (Table 2). The first component associated with 31.1% of TSV was underlain by a wide range of variables that included Ca and other basic cations (Mg and K), the root/shoot ratio, inorganic soil P pool fractions, P sorbing capacity, soil textural fractions and pH water. All plant-related variables contributed significantly to PC1 except DMY and P uptake. A stepwise regression analysis with Ca, Mg, K and exchangeable Al as independent variables explained 67.1 % of variation in root shoot ratio. The second component (PC2) was highly weighted on shoot DMY, P and N uptake, N accumulation in roots. Also significantly loaded to PC2 were acidity-related variables (soil pH and exchangeable Al) and the labile NaHCO$_3$-Pi fraction. Using a stepwise regression analysis with NaHCO$_3$-P$_i$, exchangeable Al and OC as independent variables explained 63.4% of variation in shoot DMY. The third component was highly loaded on soil organic matter components, amorphous Fe and exchangeable K, P rate and their effect on P uptake. Other significant contributors to PC3 included the silt fraction, soil pH, exchangeable Al, P uptake and shoot dry mass. The 4th component highlighted soil textural separates variation across soil types but also amorphous Fe. The last component unidimensional targeted HC extractable P.

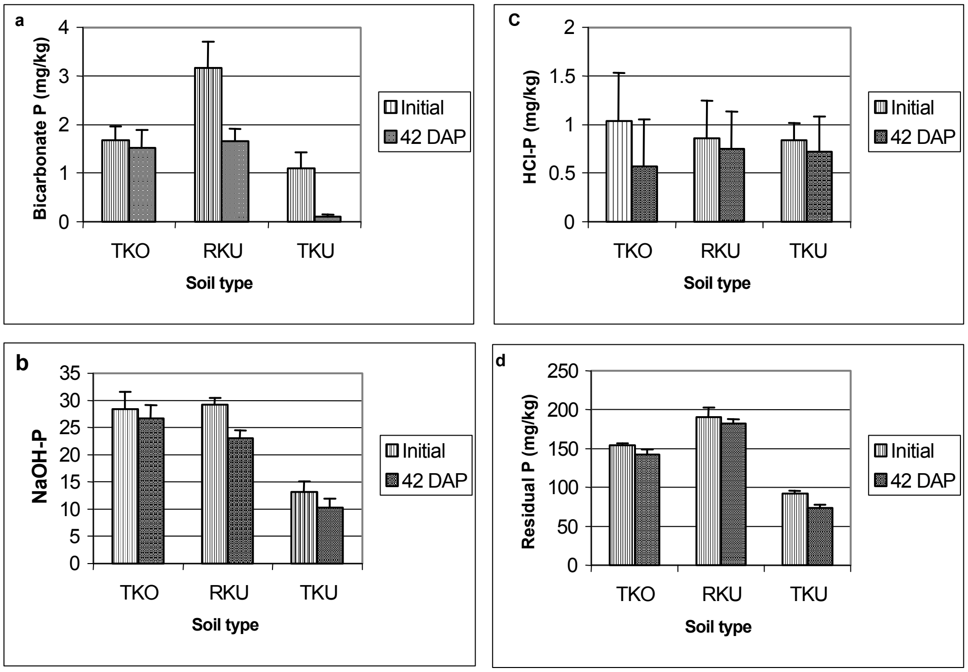

Fig. 4: Changes in P pools in exhaustive cropping

Table 2: Principal component (PC) analysis of the greenhouse experiment

Soil variables	PC1	PC2	PC3	PC4	PC5
P rate (g P pot^{-1})	0.387[δ]	0.699	0.419	0.032	0.200
DMY shoot (g pot^{-1})	-0.012	0.863	0.406	0.094	0.013
DMY root (g pot^{-1})	0.621	0.651	0.336	0.051	-0.098
root/shoot ratio	0.802	-0.342	0.034	0.014	-0.191
P uptake (g P pot^{-1})	-0.135	0.744	0.474	0.157	-0.025
N uptake (g N pot^{-1})	0.580	0.639	0.374	0.015	0.036
PAR (g P pot^{-1})	0.711	0.331	0.397	0.062	-0.266
NAR (g P pot^{-1})	0.545	0.723	0.191	-0.012	-0.099
$NaHCO_3$-Pi (mg kg^{-1})	0.654	0.527	0.136	-0.092	0.235
NaOH-Pi (mg kg^{-1})	0.860	-0.034	-0.137	-0.320	0.167
HCl-P (mg kg^{-1})	0.109	0.046	-0.013	-0.369	-0.789
Residual P (mg kg^{-1})	0.718	0.196	-0.522	-0.274	0.111
Sand (%)	-0.509	0.110	0.357	-0.740	0.125
Silt (%)	-0.294	-0.141	0.595	-0.628	-0.122
Clay (%)	0.478	-0.050	-0.436	0.747	-0.067
pH water	-0.466	0.624	-0.518	0.002	-0.007
Total N (g kg^{-1})	-0.001	-0.471	0.774	0.204	0.185
Total C (g kg^{-1})	0.299	-0.544	0.657	0.034	0.099
Ca (cmol(+) kg^{-1})	-0.812	0.255	0.340	0.281	-0.040
Mg (cmol(+) kg^{-1})	-0.745	0.523	-0.106	-0.126	0.144
K (cmol(+) kg^{-1})	-0.649	-0.069	0.698	0.071	0.010
Exch. Al (cmol(+) kg^{-1})	0.596	-0.623	0.428	-0.006	0.113
Feox (%)	0.061	0.425	-0.728	-0.402	0.184
P sorption (%)	0.746	-0.485	0.051	-0.303	0.129
Eigen value	7.46	5.78	4.62	2.26	1.05
Proportion (%)	31.09	24.08	19.26	9.41	4.38

[δ] Highlighted loadings are significant contributors to each component.

PAR : P accumulation in roots NAR : N accumulation in roots

DISCUSSION

Soil Properties and Phosphorus Interactions on Maize Growth: Partitioning soil P into conceptual pools of different bioavailability is important for following changes in soil P status over time and understanding P pool interactions with soil properties on maize growth. To this extend, the first component of the PCA with significant loadings on most soil variables is quite informative. The relationships among soil variables indicates that with increasing soil acidification, basic cations are leached and a greater fraction of primary P measured with HCl extractant transformed into NaOH and residual pools of lower bioavailability. The small size of $NaHCO_3$-Pi and HCl pools observed across all soils translates therefore the deep chemical weathering in tropical environment and low P availability [16]. As revealed by PC2, the differences of NaOH and H_2SO_4-P pools sizes across soils reflect geochemical differences in parent materials and soil age but also the relative abundance of Al- and Fe-rich minerals. The trends in inorganic P forms in the order HCl-P<$NaHCO_3$-P< NaOH <H_2SO_4-P confirms the Walker and Syers [17] model of P transformation over time. The bioassay positive responsiveness to P input for all soils confirm soil P deficiency results obtained from chemical fractionation procedures. The differential P use efficiency and dry matter yield potential across soil types translate significant interactions of inputted P and soil physico-chemical properties. Phosphorus sorption has been shown to be highly correlated with the contents of clay and total free Fe-oxide content [4]. As revealed by PCA1 (Table 2), exchangeable Al and soil pH had significant negative effects on the uptake, transport and efficient utilization of N and P and overall alteration in photosynthate allocation. Similar observations have been reported by Calba *et al* [18] and Shuman *et al*[19].The enhanced root growth observed can be considered as a maize physiological response attributed to root phosphatase activity [20] for a better exploration of the soil volume. The TKO soils derived from Precambrian metaluminous granite with a mean pH water values of 4.5 ± 0.1, low levels of Ca and Mg and high Al level represent soils with marginal potential for maize production [21]. Component 3 with the highest loading on total nitrogen and total C expresses biological and physical aspects of soils with respect to soil organic matter biomineralization rates across soil types as influenced by soil pH, clay, oxalate-extractable Fe and their effects on N and K availabilities as shown by Frossard *et al* [22].

Fertilization Effects on Soil P Status: The P fertility status of acid soils is generally affected by fertilization, the mobility and accumulation of P being controlled by sorption capacity depending on clay and Fe and Al oxides content of the soils. The change rate given by the slopes of the regression models expresses changes in P pools per unit of added P. The exponential models fitted to $NaHCO_3$-P pool indicate that changes are initially low in relation to the initial fast adsorption reactions on mineral surfaces at lower P rates. At higher P input, the adsorption sites are progressively saturated resulting in sharp increase in soil P concentrations. Comparisons across soils indicate that amount of inputted P were recorded from the $NaHCO_3$-Pi and NaOH-Pi pools in RKU and TKO soils with lighter texture. Similar observations were reported from soils from the Rothamsted experimental station [4]. The emergence of NaOH-Pi and residual P as the largest P pools reflects the overall geochemical dominance on P cycling processes. The enrichment of these two pools during fertilization indicates that a substantial portion of P fertilizers is rapidly converted under acid soil conditions to pools of lower bioavailability. This finding is in line with most previous P studies by Selles *et al* [23]. The decrease in NaOH-Pi across all control treatments is suggestive of secondary P becoming plant available [4]. The HCl-P pool is believed to represent soil P associated with primary minerals such as apatite or Ca-P. The absence of a clear pattern upon fertilization is in line with results by Selles *et al* [23] who found no effect of P fertilizer on HCl-P pool on a Brazilian oxic Haplustults. The mean slopes of NaOH-Pi lines was lower than those of H_2SO_4-P indicating that it was the greatest sink in acid tropical soils. The gradual build-up of residual P upon fertilization and its decline in exhaustive cropping has been described by Guo *et al* [24].

CONCLUSION

The present pot experimental study indicates acid soils in southern Cameroon are inherently low in labile P but present the same trend in P pools. They differed significantly in their secondary and residual pools P. Phosphorus fertilitisation induced differential changes in inorganic pools the most enriched being the NaOH-Pi and H_2SO_4-Pi. The multivariate statistical approach permitted a more synthetic interpretation, providing information on edaphic constraints affecting phosphorus use efficiency and correlatively maize potential growth in acid soils. These constraints include i) Ca and other basic cations deficiencies conducive to enhanced root growth, reduced P uptake and overall alteration in photosynthate allocation, ii) soil acidity and Al toxicity that reduces nutrient uptake and biomass production and lastly iii). N availability as related to organic matter decomposition. The highlighted constraints are acute in oxisols derived from metaluminous granitic materials and need to be alleviated in order to improve P fertilizer efficiency. Liming appears as the classical solution for raising soil pH while at the same time precipitating exchangeable Al. This practice may reveal financially prohibitive for most resource-poor farmers of the humid tropics. To this respect, indigenous practices combining fallowing and partial burning of the vegetation remains an ecologically sound practice in the short run in low populated areas. Screening for Al-tolerant plant genotypes remains a sound research pathway for enhancing food crop production in vast areas of acid soils of the humid tropics.

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