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Application of Expert Systems to Study of Acid Soils in Rwanda

Charles F. Yamoah and James R. Burleigh

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APPLICATION OF EXPERT SYSTEMS TO STUDY OF ACID SOILS IN RWANDA

Charles F. Yamoah and James R. Burleigh
Farming Systems Research Program (FSRP), BP 625, Kigali, Rwanda

ABSTRACT

Two expert programs, Soil Fertility Capability Classification (SFCC) and ACID4, were used to assess fertility of some soils in the highland region of Rwanda. Soils were grouped with respect to altitude, rainfall and parent material into three agroecological zones. Soils in zone 3 with high rainfall, low altitude and underlain by quartzite-schists complex were lower in fertility and more acidic than their counterparts in zones 1 and 2. Nitrogen (N), phosphorus (P) and potassium (K) were generally deficient. Calcium (Ca) and magnesium (Mg) were considered as borderline cases and are expected to fall below acceptable levels after a few years of cultivation. The SFCC identified clayey (>35% clay) and acidic (% Aluminum (Al) saturation between 10 and 60) topsoils with low K reserves (exchangeable K < 0.2 meq/100g) as the dominant fertility class Crop residue management, agroforestry and green manure systems are recommended in addition to P and K fertilization to alleviate nutrient deficiency problems. Soil acidity was associated with exchangeable Al, and Al saturation was > 50% at pH < 5.2. Base saturation was negatively correlated with Al saturation and positively related to Ca+Mg. Therefore, liming to supply Ca and Mg may reduce exchangeable Al and improve ECEC and nutrient retention. Lime requirement ranged from 0 to 6 tons CaCO3/ha and was directly proportional to exchangeable Al (r= 0.95**) and inversely related to pH (r= - 0.73**). Results from a lime prediction equation: Y = 1.332 * Al - 0.11 computed for soils in the region concurred with those of other workers.

INTRODUCTION

Rwanda is a small, landlocked country under severe population pressure. Farming is intensive, and fields are concentrated on steep hillsides. This results in soil acidity, low fertility, accelerated erosion and low crop yields. According to Vander Zaag et al. (1984), 36% of subsoil samples in Rwanda had pH < 5. Nizeyimana and Bicki (1988) reported a pH range of 3.9 to 5.5 for some mountain soils in Rwanda. Neel and De Prins (1974) recorded pH 4.69 for soils in the high-altitude zone of Rwanda.

Knowledge of factors that cause soil acidity and consequent nutrient deficiencies is important for soil fertility management. Properties and management of acid tropical soils have been studied by several researchers (Sanchez, 1976; Buol et al., 1980; Juo and Ballaux, 1977; Krampath, 1984; Fox, 1974; Agboola, 1981; Lal et al., 1979; Nye and Greenland, 1960). Experiences accumulated by some of these scientists involved in tropical soils research for over two decades led to the development of 1) soil fertility capability classification (SFCC) Boul et al. (1988) and 2) ACID4 (Tropsoils, 1987) expert systems.

This study applied the SFCC and ACID4 computer programs to assess soil fertility in the highland region of Rwanda.

MATERIALS AND METHODS

Site Description and Soil Sampling

The study was conducted in the Buberuka Highlands and Central Plateau agroecological zones of Rwanda. Soils are classified in the USDA system as Oxisols (RRAM, 1987; Franzel et al., 1985) and are developed from schists, quartzite and granite parent materials. Rainfall is bimodal and decreases from the Central Plateau in the south to the Buberuka Highlands in the north (Fig. 1). Elevation ranges from 1500 m in the Central Plateau to over 2600 m in the Buberuka Highlands. Mean monthly temperature is higher for the Central Plateau (>22 C) than for the Buberuka Highlands (<13-17 C). Detailed information on farming systems in the region is presented by Franzel et al. (1985). The Farming Systems Research Program (FSRP) is located in this region.

Soils were sampled from fields of farmers who collaborate with FSRP in testing agroforestry and wheat interventions. In all, 110 bulk samples were collected and analyzed. A bulk sample consisted of 10 core samples taken with a soil auger at 0- to 15-cm depth. Figure 1 shows agroecological zones and sampling sites in the project area.

Soil Analytical Methods

Methods for soil analysis were as follows:

1) pH in water (1:1 soil to water ratio);
2) hydrometer method for sand, silt and clay;
3) organic carbon by Walkley-Black method;
4) exchangeable acidity extracting (Al+H) with N KCl followed by titration with NaOH and HCl;
5) total nitrogen (N) by macro-Kjeldahl method;
6) available phosphorus (P) by Bray P1 method;
7) exchangeable cations Ca, Mg, K and Na by extraction with 1 N NH_4OAC solution at pH 7;
8) effective cation exchange capacity (ECEC) as sum of Ca+Mg+K+Na+Al+H;
9) base saturation calculated as Ca+Mg+K+Na/ECEC * 100; and
10) aluminum (Al) saturation as exchangeable Al/ECEC * 100.

Data Analysis

First, the project area was divided into three agroecological zones based on elevation, rainfall and parent material as follows:

1) High elevation, > 2000 m
   Low rainfall, < 1200 mm
   Parent material: granite and schists complex

2) Medium to high elevation, 1800 - 2000 m
   Rainfall between 1200 and 1400 mm
   Parent material: granite and schists complex

3) Low elevation, 1500 - 1800 m
   High rainfall, > 1400 mm
   Parent material: quartzite and schists complex

Temperature is inversely related to altitude and decreases in the following order: zone 3 > zone 2 > zone 1. Soil properties among the three zones were compared using analysis of variance (ANOVA) with LSD = (0.05). The number of samples for zones 1, 2 and 3 were 24, 69 and 17, respectively. Relationships between soil properties were established by ordinary least squares (OLS) regression analysis.

Soil data for each sample was input into the SFCC program separately to determine the fertility capability class per site. Frequency distribution was then examined to identify dominant fertility classes for the region. Lime requirement for the soils was estimated with the ACID4 program. Data for each sample was fed into the program separately to compute the lime requirement of each field. An Al-sensitive crop (bean) was chosen as the test crop in the ACID4 model. Using the estimated lime requirement as the dependent variable, regression analyses were run with Al and pH as independent variables to obtain prediction equations. Computations were done on an IBM-AT micro-computer. SPSS and LOTUS software were used for the statistical analyses.

RESULTS AND DISCUSSION

Fertility of Soils in the Three Agroecological Zones

Fertility levels of soils in the three agroecological zones are shown in Table 1. The soils were very low to low in all major nutrients. Nitrogen, P and potassium (K) were below levels required for normal crop production (Singh, 1979). Vander Zaag et al. (1984) made similar observations during a survey of soils in 12 agroecological zones in Rwanda. Current levels of calcium (Ca) and magnesium (Mg) are barely sufficient for normal crop production and are expected to fall below acceptable ranges following a few years of cultivation without application of soil amendments. There are a few sites, however, where Ca and Mg were more than adequate for crop production. These are seen in the range values of the nutrients. To substantiate, P levels in zone 2 ranged from a very low value of 0.35 to a high value of 105.00 ppm. A similar trend holds for Ca and K in the same agroecological zone.

Average soil pH for all the zones was less than 5.5, indicating possible Al toxicity for Al-sensitive crops. Exchangeable acidity (Al+H) was more than 2 meq/100g. Mean Al saturation was below 50%, but the range shows values greater than 70% (Table 1). Aluminum saturation levels encountered in these soils affect performance of beans and other Al-sensitive legumes more than maize and potatoes (Krampath, 1984; Krampath, 1970).

Effective cation exchange capacity (ECEC) measures the ability of soils to retain nutrients. The low ECEC of the soils implies that nutrients are liable to leaching. Leaching of nutrients is generally undesirable, but in the FSRP zone some movement of Ca and Mg down the soil profile may help remove subsoil acidity and facilitate tree crop establishment. In zones 1 and 2, low environmental temperatures retard germination and growth of crops; therefore, leaching may be minimized by applying basal fertilizer after germination. There is little justification for increasing ECEC of acid soils if the exchange sites are occupied by Al. Liming should precede attempts to raise ECEC with practices such as addition of organic materials.

Organic carbon was low with the exception of soils in the valley swamps where the value exceeded 10%. Exchangeable H increases with increase in organic matter ($r=0.39^{**}$) and aggravates acidity problems. The role of organic carbon is questionable in acid soils where Al dominates the exchange complex (Sanchez and Miller, 1986; Lopes and Cox, 1977).

In general, soils of zone 3 were lower in all nutrient elements than those of zones 1 and 2. Mean percent Al saturation for zones 1, 2 and 3 were 22.37, 22.39 and 46.80, respectively. Available P for the respective zones were 8.39, 6.64 and 2.44 ppm, which points to possible P fixation by Al in zone 3. Correction of P deficiency of these soils in the long term demands application of initial high P rates to saturate the P fixing sites, followed by use of reduced rates for maintenance. The initial P rate depends on soil clay content (i.e, 10 kg P_2O_5 for every 1% clay). Based on this formula, about 330 kg P_2O_5/ha is recommended for the acid soils of zone 3 (Buol et al., 1983).

Rainfall and temperature are higher in zone 3 than in zones 1 and 2. These two factors are responsible for weathering, leaching and soil erosion. Besides, soils of zone 3 are partly derived from quartzite, which is low in nutrient elements. The survey conducted by Vander Zaag et al. (1984) revealed a higher desilication rate in the Central Plateau area, which embraces zone 3, than in the Buberuka Highlands, where zones 1 and 2 are located. Desilication, analogous to weathering and leaching, is a process that renders soils acidic and deprives them of essential nutrients.

Soil Fertility Capability Classification

Eight main fertility classes were recognized following the system developed by Sanchez et al. (1982).

1) Clayey topsoils, acidic and with low K reserves
2) Clayey topsoils, acidic and with adequate K reserves
3) Clayey topsoils, non-acidic with low K reserves
4) Clayey topsoils, non-acidic and with adequate K reserves
5) Loamy topsoils, acidic and with low K reserves
6) Loamy topsoils, acidic and with adequate K reserves
7) Loamy topsoils, non-acidic and with low K reserves
8) Loamy topsoils, non-acidic and with adequate K reserves.

The frequency distribution of these classes is shown in Fig. 2. Aside from the above class distribution, 6% of the soils had Al toxicity, 32% had low cation exchange capacity, and one site had lime ($CaCO_3$) deposit. In the aggregate, 63% of the soils had clayey topsoil, 47 had loamy topsoil, 55% had low K reserves, and 75% were acidic. Soil acidity is connected with high exchangeable Al and low P availability.

Several factors account for low K and other nutrient reserves in acid soils. Among them, the following seem to apply under Rwandan conditions. First is the low buffering capacity of the soils. The soil mineralogy is dominated by low activity kaolinitic clays that have fewer cation exchange sites than 2:1 clays. Increasing CEC of these soils by addition of organic materials would not help retain K because of the low affinity of organic matter for K ions (Uribe and Cox, 1988).

Second, removal of crop residues after harvest is a common farming practice in Rwanda. The residues are composted, used as animal feed or burnt as fuel. Crop residues are rich in K and grains rich in P. By exporting residues and edible portions of food crops outside the fields, K and P deficiencies gradually develop. Composted materials are usually devoid of K because of rapid leaching of the element during the composting process (Bandy and Nicholaides, 1983). This makes application of compost less meaningful with respect to K fertilization.

Third, for obvious reasons, Rwandan farmers, like many others in Africa, seldom apply inorganic fertilizers to their cropped fields. Rather, animal manure is commonly used, albeit in insufficient quantities and low quality. This also contributes to decline in soil productivity over time. The fertility capability assessment recommended application of P and K fertilizers as well as liming to supply Ca and Mg. In addition to the above, agroforestry and green manuring may help recycle immobilized and leached nutrients and consequently minimize soil fertility decline. Varietal screening for Al toxicity and P deficiency may be a low-cost approach to improving productivity of these soils. The sites that had Al saturation > 60% may be suitable locations for screening cultivars for Al tolerance. Also, the lime deposit could be explored and mined to provide liming material for farmers in the region. On-going research demonstrates possible bean yield enhancement with application of the locally mined lime

Relationships Between Some Soil Properties

pH and aluminum saturation. Soil pH and Al saturation are negatively correlated (Fig. 3). Percent Al saturation exceeded 30 for pH < 5.4 in most of the samples. Above pH 6, Al saturation dropped to zero. This trend agrees with results of Vander Zaag et al. (1984). Thirteen percent of the soils had pH > 6, and < 2% had pH > 7. Thus, liming is necessary for cultivation of beans and allied crops intolerable to Al saturation > 30%. The lime provides Ca and Mg to the food crops and maintains stability of the soil aggregates as well (Alegre and Cassel, 1986).

Al saturation and basic cations. As generally expected, base saturation is inversely correlated with Al saturation (Fig. 4). At 60% base saturation, Al saturation was below 30%. Seventy percent base saturation reduced Al saturation to < 20% and created a medium conducive to growth of most crops. Ca + Mg is positively correlated with base saturation (Fig. 5) and inversely related to Al saturation (Fig. 6). This demonstrates the potential of dolomitic lime to suppress Al toxicity. When exchangeable Ca + Mg = 8 meq/100g, base saturation reached almost 100%, and Al toxicity became non-existent. Wood ash is a substitute for dolomitic lime where financial constraints and logistics preclude acquisition of the latter (Sanchez et al., 1983; Juo and Ballaux, 1977).

Soil organic matter controls Al toxicity by chelating exchangeable Al. But the effect is short-lived and reverses after a few months as the organic matter decomposes and releases Al from the organo-Al complex (Wade and Sanchez, 1983; Sanchez et al., 1983). It is yet to be determined, however, whether a continuous supply of organic materials as in alley cropping systems would reduce exchangeable Al to acceptable levels. Certainly, farmers would opt for this method to check Al toxicity if it is proven to be effective and lasting.

Effective cation exchange capacity, organic carbon, N and P. The relationship between pH and ECEC appeared negative below pH 5.2 (Fig. 7). Above pH 5.2, correlation between pH and ECEC became positive. At pH < 5.2, exchangeable Al dominated the exchange complex, neutralized exchange sites and consequently lowered the ECEC. Similar results were obtained by Pratt and Bair (1962) for some acid soils in California.

Correlation between organic carbon and ECEC was weak (r=0.29*). The relationship between ECEC and organic carbon improved slightly at pH > 6. Coleman and Thomas (1967) attributed this phenomenon to counteracting of negative sites of organic carbon by exchangeable Al. Due to similar reasons,

Lopes and Cox (1977) found a negative correlation between organic matter and ECEC at pH < 5 and a positive but weak relationship for pH between 5.0 and 5.5 for acid soils in Brazil.

Strong correlation between Ca+Mg and ECEC is indicative of the potential of raising ECEC of the soils by liming. ECEC is also proportional to available P (r=.63**), K (r=.35**) and N (r=.29**), suggesting higher nutrient retention with increased ECEC.

Organic carbon is correlated with N (Fig. 8) and P (r=.34**). Thus, removal of top soil rich in organic carbon is tantamount to ridding the soil of its fertility. Erosion removes top soil; therefore, by controlling erosion, topsoil fertility may be preserved. In terms of contribution to ECEC, organic matter was more effective than clay. Thus loss of topsoil organic matter through erosion ultimately leads to further decline in ECEC. The direct proportionality between organic carbon and N supports employment of organic materials from herbaceous and shrub legumes as N sources for crop production.

Lime Requirement

Lime requirement as a function of exchangeable Al and pH is shown in Fig. 9 and 10, respectively. Lime requirement for the soils ranged from 0 to 6 t $CaCO_3$/ha and is directly related to exchangeable Al and inversely proportional to pH. The correlation coefficient for the equation predicting lime requirement from exchangeable Al was r = 0.95** as opposed to r = 0.73** for pH. Exchangeable Al may therefore be a better predictor of lime requirement of the soils than pH (Krampath, 1970; Reeve and Sumner, 1970). As a tool for making routine assessment of lime needs by field extension workers, soil pH may be preferred to exchangeable Al because pH is easy to measure. Correlations between clay, organic carbon and lime requirement were not significant.

Estimated lime requirement (Y) using the prediction equation from this study, Y = 1.332 * Al - 0.11 compares favorably with those developed by Vander Zaag et al. (1984) and Krampath (1970) (Table 2).

In most cases, liming is required once in every three years (Tropsoils, 1987). The final decision on lime requirement, however, rests on production economics.

CONCLUSIONS

The SFCC and ACID4 expert programs were used to diagnose soil fertility problems and make lime recommendations for some acid soils of the Rwandan Highlands. According to the SFCC, 75% of the soils were acidic and 55% low in K reserves. Soils of the low-altitude, high-rainfall Central Plateau region were poorer in fertility and more acidic than those in the Buberuka Highlands. Soil acidity was associated with high exchangeable Al and Al saturation that exceeded 50% at pH < 5.2.

There was a significant and negative correlation between base saturation and Al saturation as well as between exchangeable Ca+Mg and Al saturation, highlighting the potential of lime to reduce exchangeable Al in these soils.

Organic matter was generally low except in the valley soils. Organic matter was positively related to ECEC, but the relationship was not significant. The relationship between ECEC and pH seemed negative at pH < 5.2. This again emphasizes the need for liming to improve nutrient retention of the soils and to provide Ca and Mg to food crops. Lime is available locally in the Ruhengeri Province and parts of the project area that fall within the same Province.

The amount of lime required to raise productivity of the soils is more closely related to exchangeable Al than to pH. Results from a lime requirement prediction equation determined in this study were comparable to those obtained by other workers. Soil pH may serve as a good indicator of lime requirement in regular extension work.

The SFCC and ACID4 expert programs provide quick and cost-effective means of evaluating soil fertility-related problems and prescribing remedial measures to overcome them. They are particularly useful as guides in situations where lack of manpower and funds limit basic agronomic research. The programs are simple to use and are run by data obtainable through routine analysis. Farming systems research scientists could employ them as instruments for diagnosing soil-related constraints prior to on-station experimentation and on-farm testing.

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LITERATURE CITED

1. Agboola, A.A. 1981. The effect of different soil tillage and management practices on the physical and chemical properties of soil and maize yield in a rain forest zone of Western Nigeria. Agron. J. 73:247-251.

2. Alegre, J.C. and D.K. Cassel. 1986. Effect of land-clearing methods and postclearing management on aggregate stability and organic carbon content of a soil in the humid tropics. Soil Sci. 142(5):289-295.

3. Bandy, D.E. and J.J. Nicholaides. 1983. Composting and mulching. In agronomic-economic research on soils of the tropics: Annual report for 1980-81. North Carolina State University, Raleigh.

4. Buol, S.W., F.D. Hole and R.J. McCracken. 1980. Soil genesis and classification. 2nd ed. Ames, Iowa: Iowa State Univ. Press.

5. Buol, S.W., P.A. Sanchez and G.S. Buol. 1988. Fertility Capability Classification (FCC). Draft computer program for editing. North Carolina State University, Raleigh, USA.

6. Coleman, N.T. and G.W. Thomas. 1967. The basic chemistry of soil acidity. In: Soil acidity and liming, R.W. Pearson and F. Adams, eds. Agron. 12:1-41.

7. Fox, R.L. 1974. Examples of anion and cation adsorption by soils of tropical Americ. Trop. Agric. (Trinidad) 51:200-210.

8. Franzel, S., K.B. Paul, B. Yates and D.E. Voth. 1985. Preliminary diagnostic survey of five communes of Ruhengeri Prefecture, Rwanda. Staff paper, University of Arkansas, Fayetteville, Arkansas, USA.

9. Juo, A.S.R. and J.C. Ballaux. 1977. Retention and leaching of nutrients in a limed Ultisol under cropping. Soil Sci. Soc.Am J. 41:757-761.

10. Krampath, E.J. 1970. Exchangeable Al as a criterion for liming leached mineral soils. Soil Sci. Soc. Am. Proc. 34:252-254.

11. Krampath, E.J. 1984. Crop response to lime on soils in the tropics. In: F. Adams, ed. Soil acidity and liming. Agronomy Monograph no. 12 (2nd Edition).

12. Lal, R., G.F. Wilson and B.N. Okigbo. 1979. Changes in properties of an Alfisol produced by crop covers. Soil Sci. 6:377-382.

13. Lopes, A.S. and F.R. Cox. 1977. A Survey of fertility status of surface soils under Cerrado vegetation in Brazil. Soil Sci. Soc Am. J 41:742-747.

14. Neel, H. and H. De Prins. 1974. L'amelioration des sols des region d'altitude. Institut des Science Agronomiques du Rwanda (ISAR). Note Technique no. 11.

15. Nizeyimana, E. and T.J. Bicki. 1988. Soils and soil-landscape relationships in the mountainous region of Rwanda, East Central Africa. Agronomy abstract, pp.263.

16. Nye, P.H. and D.J. Greenland. 1960. The soils under shifting cultivation. Techn. Comm. 51: Commonwealth Bureau of Soils, Harpenden.

17. Pratt, P.F. and F.L. Bair. 1962. Cation-exchange properties of some acid soils of California. Hilgardia 33:686-706.

18. Reeve, N.T. and M.E. Sumner. 1970. Lime requirement of Natal Oxisols based on exchangeable aluminum. Soil Sci. Soc. Am. Proc. 34:595-598.

19. Ruhengeri Resource Analysis and Management (RRAM) Project. 1987. Ruhengeri and its resources. An environmental profile of the Ruhengeri Prefecture. United States Agency for International Development (USAID), Kigali, Rwanda.

20. Sanchez, P.A. 1976. Properties and management of soils in the tropics. New York: Wiley.

21. Sanchez, P.A., W. Couto and S.W. Buol. 1982. The fertility capability soil classification system interpretation, applicability and modification. Geoderma 27:283-309.

22. Sanchez, P.A., and R.H. Miller. 1986. Organic matter and soil fertility management in acid soils of the tropics. Paper presented at 13th congress of the International Society of Soil Science (Hamburg) 6:609-625.

23. Sanchez, P.A., J.H. Villachica and D.E. Bandy. 1983. Soil fertility dynamics after clearing a tropical rainforest in Peru. Soil Sci. Soc. Am. J. 47:1171-1178.

24. Singh, B.R. 1979. Nutrient availability and optimum nutrient element levels in soils for crops under agroforestry conditions. In: H.O. Mongi and P.A. Huxley, eds. Soils research in agroforestry: Proceedings of an expert consultation. ICRAF, Nairobi.

25. Tropsoils. 1987. ACID4: An expert system to manage soil acidity in the humid tropics. The Centre for Soils Research, Bogor, Indonesia; Univ. of Hawaii and North Carolina State Univ.

26. Uribe, E. and F. R. Cox. 1988. Soil properties affecting the availability of potassium in highly weathered soils. Soil Sci Soc. Am. J. 52:148-152.

27. Vander Zaag, P., R.S. Yost, B.B. Trangmar, K. Hayashi and R.L. Fox. 1984. An assessment of chemical properties for soils of Rwanda with the use of geostatistical techniques. Geoderma 34:293-314.

28. Wade, M.K. and P.A. Sanchez. 1983. Mulching and green manure applications for continuous crop production in the Amazon basin. Agron. J. 75:39-45.

Table. 1. Soil properties for three agroecological zones in Rwanda.

Soil Property	Zone 1	Zone 2	Zone 3
Sand (%)	ab[1]	b	a
Mean (X)	35.45	30.13	38.35
Standard error (SE)	2.68	1.35	2.36
Range (R)	16-56	14-63	22-52
Clay (%)	a	a	b
X	40.00	40.37	33.00
SE	2.27	1.00	1.19
R	24-59	19-59	41-50
pH (water)	ab	a	b
X	5.29	5.39	5.01
SE	0.12	0.07	0.07
R	4.10-6.30	4.28-7.4	4.4-5.47
Extra. Al (meq/100 g)	b	b	a
X	1.80	1.74	2.77
SE	0.34	0.18	0.20
R	0.03-6.35	0.00-6.78	1.05-4.35
Organic carbon (%)	a	b	b
X	2.8	2.06	2.01
SE	0.50	0.08	0.15
R	1.20-10.98	0.5-4.79	1.1-3.4
Exchangeable sodium (meq/100g)	ab	a	b
X	0.12	0.21	0.03
SE	0.03	0.03	0.00
R	0.03-0.64	0.01-1.22	0.02-0.07
ECEC (meq/100g)	a	a	b
X	8.78	7.77	6.18
SE	0.57	0.30	0.25
R	4.8-17.09	1.91-23.82	4.59-7.87
Aluminum saturation (%)	b	b	a
X	23.37	22.39	46.08
SE	4.37	2.13	3.66
R	0.17-72.65	0.00-71.89	13.85-77.97
Base saturation (%)	a	a	b
X	69.76	69.72	45.75
SE	5.36	2.51	3.99
R	17.05-99.18	15.69-99.20	10.72-80.21
Exchangeable hydrogen (meq/100g)			
X	0.39	0.39	0.47
SE	0.07	0.03	0.04
R	0.00-1.6	0.02-1.07	0.18-0.83
Total nitrogen (%)			
X	0.25	0.22	0.24
SE	0.03	0.00	0.01
R	0.09-0.78	0.09-0.36	0.13-0.50
Available phosphorus (ppm)			
X	8.39	6.64	2.44
SE	2.04	1.96	0.68
R	1.05-39.55	0.35-105.00	0.7-11.55

continued

Table. 1 continued.

Soil Property	Zone 1	Zone 2	Zone 3
Exchangeable calcium (meq/100g)	a	a	b
X	4.63	3.62	2.07
SE	0.63	0.29	0.25
R	0.95-13.50	0.8-19.36	0.30-4.44
Exchangeable magnesium (meq/100g)	a	a	b
X	1.38	1.09	0.63
SE	0.20	0.06	0.07
R	0.30-4.05	0.29-2.53	0.16-1.51
Exchangeable potassium (meq/100g)	ab	a	b
X	0.30	0.47	0.15
SE	0.05	0.06	0.06
R	0.06-1.02	0.05-2.00	0.06-1.26

[1]Means with different letters differ significantly at P=0.05.

Table 2. Estimated lime requirement for Rwandan soils from ACID4 and other methods.

		Lime requirement ($CaCO_3$ t/ha)		
pH	Exch.Al (meq/100g)	Incubation[1]	Krampath[2]	ACID4[3]
4.4	2.1	2.4	3.2	2.68
4.6	1.4	1.4	2.1	1.75
4.8	2.0	4.6	3.0	2.55
4.7	2.4	2.2	3.6	3.08
4.1	0.9	1.8	1.4	1.08
4.5	3.3	3.2	5.0	4.28
4.8	1.9	1.8	2.8	2.42
4.1	4.6	2.0	6.9	6.01
3.7	4.5	6.8	6.8	5.88
3.9	2.0	3.8	3.0	2.55
4.3	2.1	5.1	3.2	2.68
3.7	3.1	5.5	4.6	4.01
$\bar{X}$ 4.3	2.5	4.1	3.8	3.24

[1]Vander Zaaq et al., 1984.
[2]Krampath, 1970.
[3]Y = 1.332 * Al - 0.11, present study.

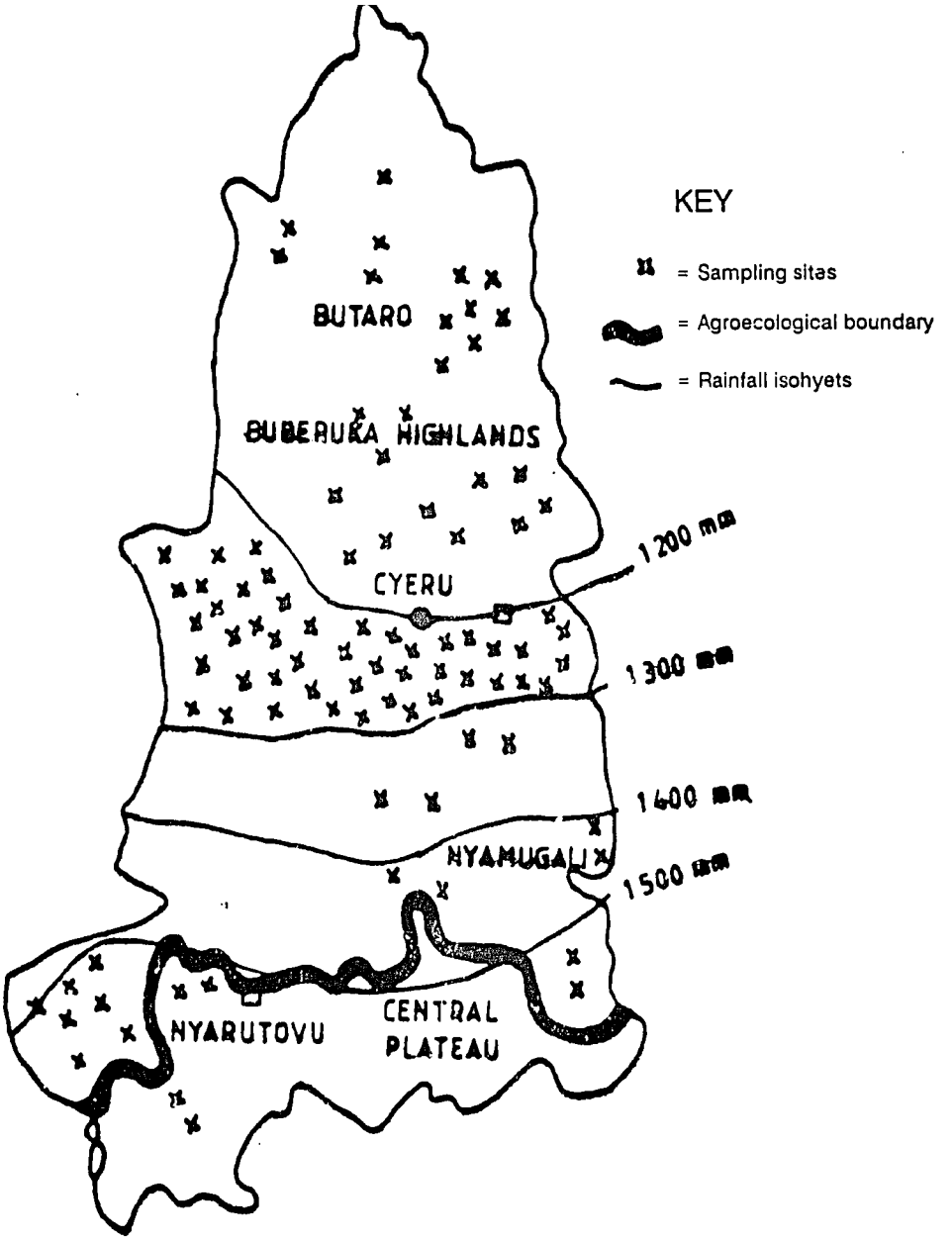

Fig. 1. Map of the FSRP area showing sampling sites. Scale = 1/290,000.

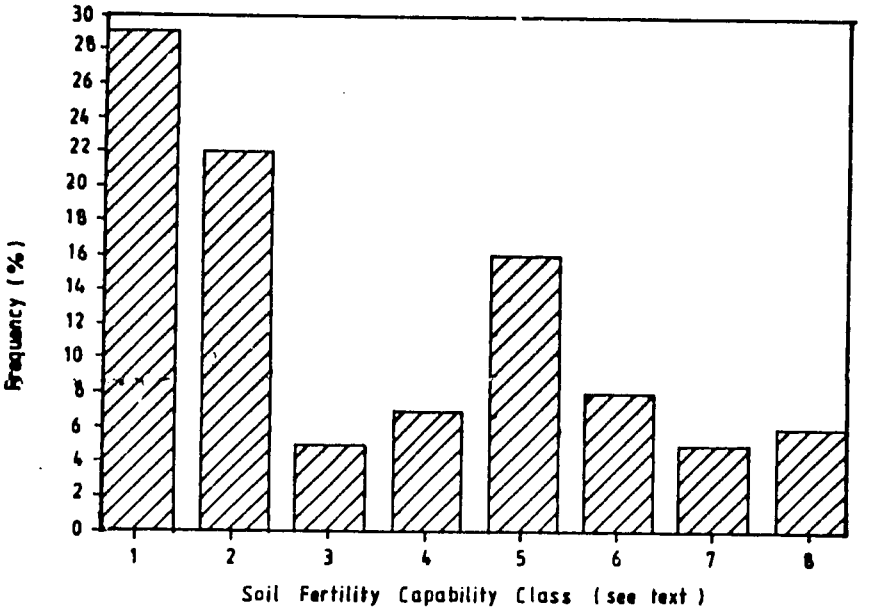

Fig. 2. Frequency distribution of fertility capability class (FCC).

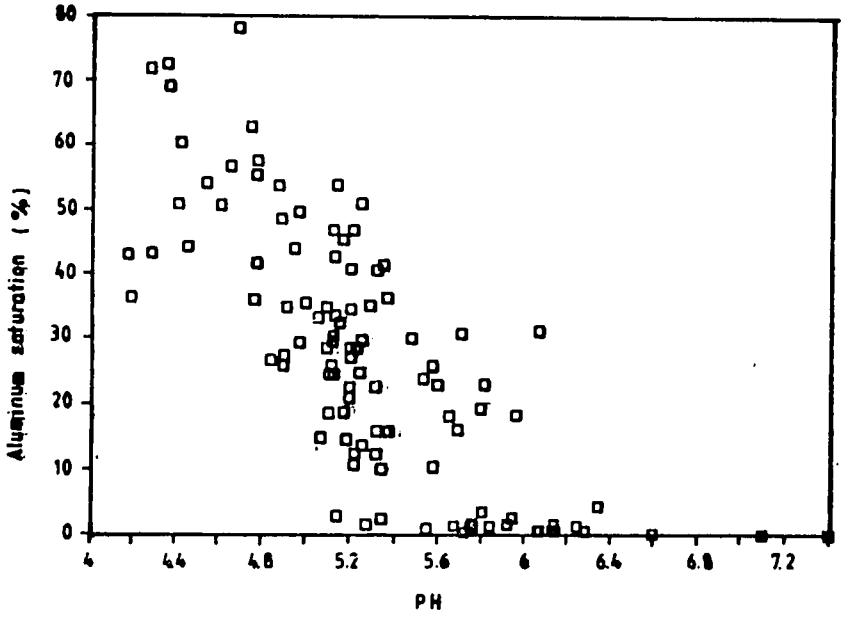

Fig. 3. Aluminum (Al) saturation as influenced by soil pH.

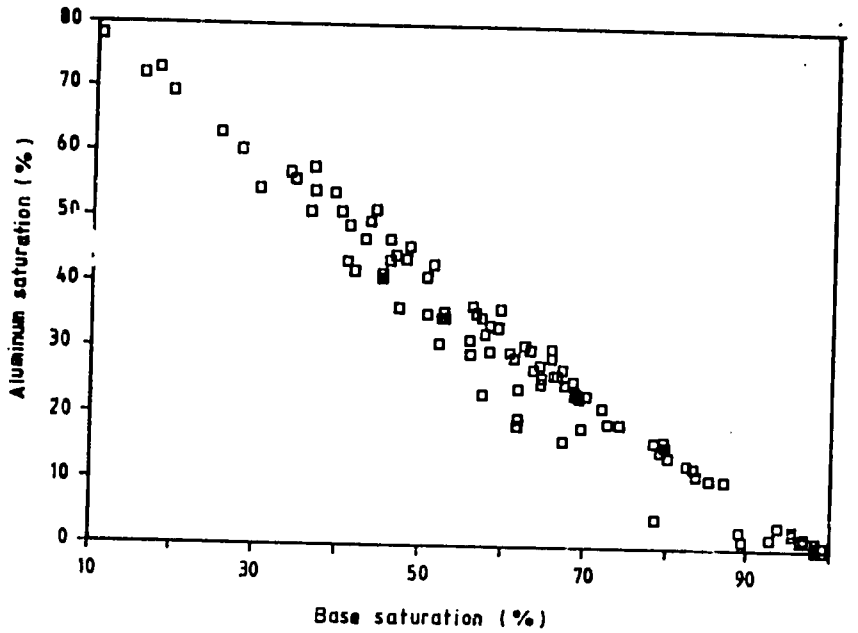

Fig. 4. Relationship between base saturation and aluminum (Al) saturation.

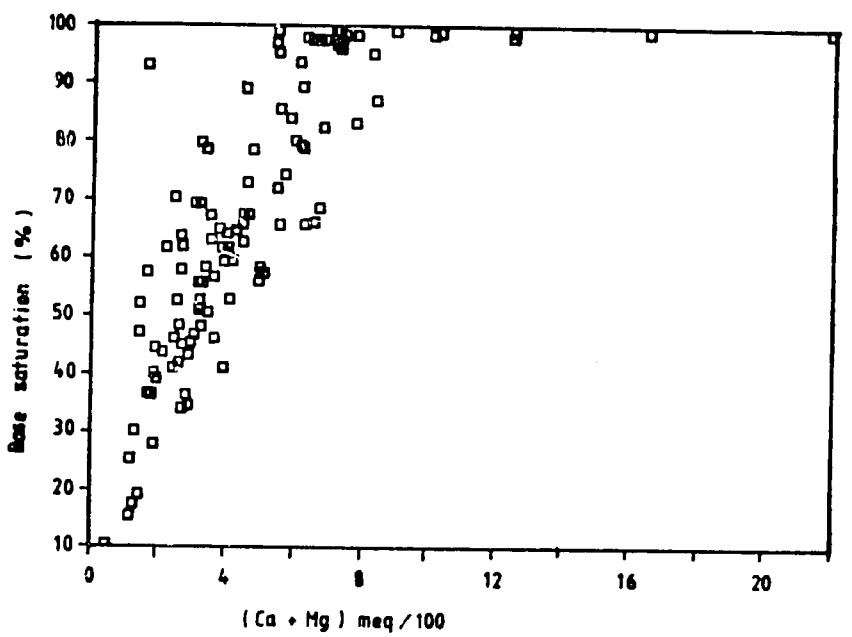

Fig. 5. Relationship between calcium (Ca) + magnesium (Mg) and base saturation.

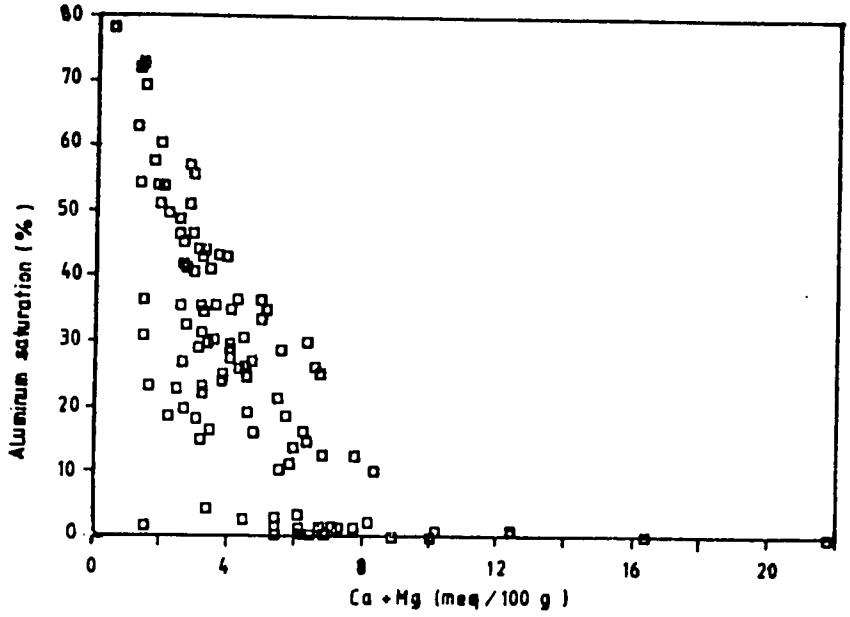

Fig. 6. Relationship between calcium (Ca) + magnesium (Mg) and aluminum (Al) saturation.

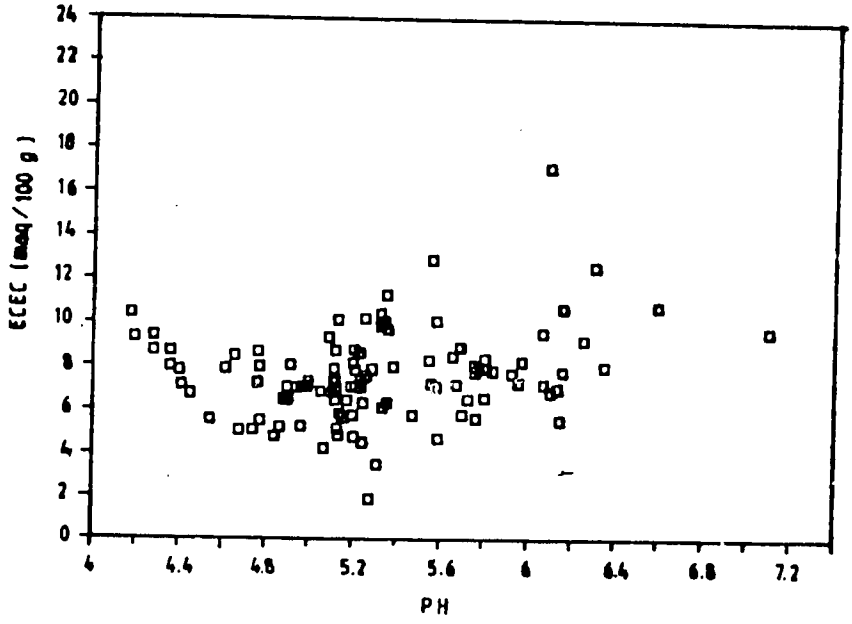

Fig. 7. Relationship between pH and effective cation exchange capacity (ECEC).

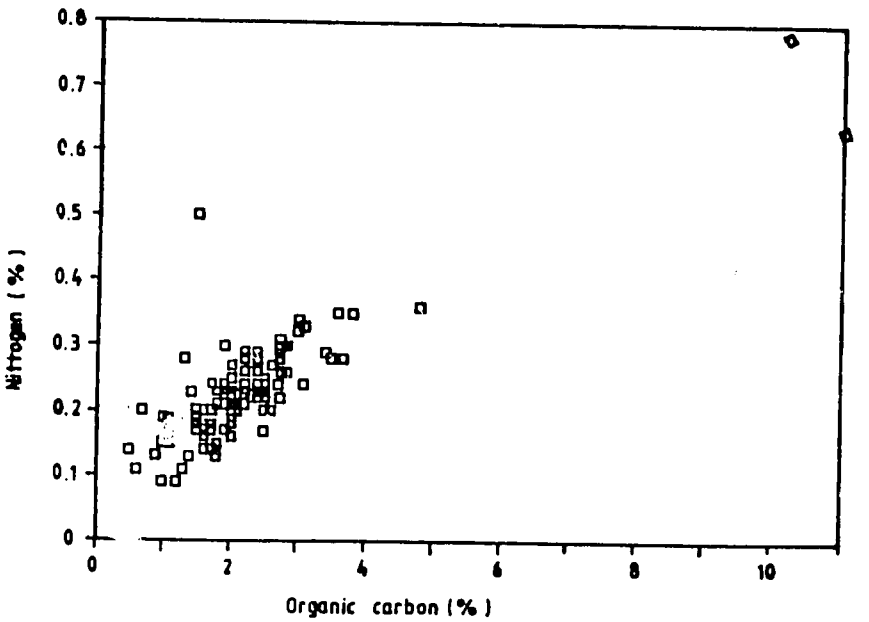

Fig. 8. Relationship between organic carbon and total nitrogen (N).

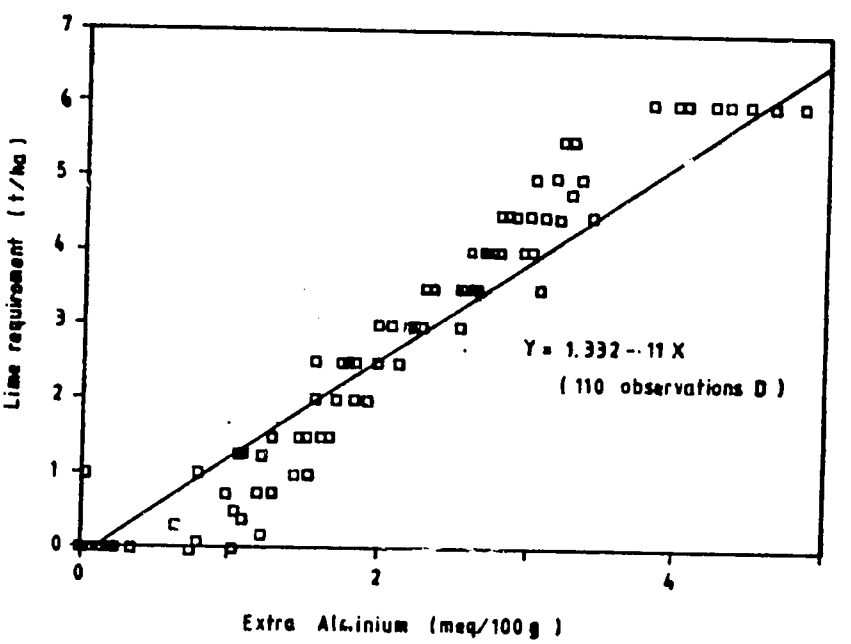

Fig. 9. Lime requirement as influenced by extractable aluminum (Al).

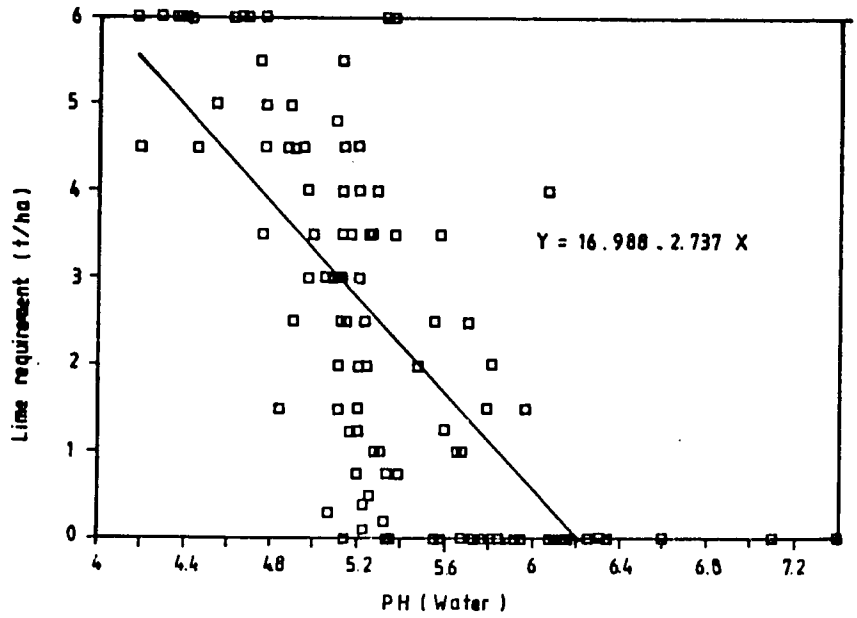

Fig. 10. Lime requirement as influenced by soil pH.