

SOIL NUTRIENT STATUS, SPATIAL VARIABILITY OF SOIL
CHEMICAL PROPERTIES AND FERTILIZATION REQUIREMENTS
IN CABO DELGADO, NAMPULA AND MANICA PROVINCES OF
MOZAMBIQUE

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAI'I IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
TROPICAL PLANT AND SOIL SCIENCES

DECEMBER 2004

BY

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ACKNOWLEDGMENTS

There many people that I would like to express my gratitude to for their support during my studies. I would to express my special gratitude to my supervisor, Dr. Russell Yost, for his advice hard work during soil sampling under very difficult conditions and for always getting comments back to me in record time.

I would like to thank Dr. Goro Uehara, Dr. James Silva for their advice regarding data analysis and laboratory work.

I gratefully acknowledge Dr. Thomas Crawford, Mrs. Joan Frederick, and Dr. John Yohe from INTSORMIL for their support and coordination of my financial assistance. Appreciation is extended to the USAID mission in Mozambique for the financial support it provided.

I would like to thank Dr. Deenik, Dr. Hue, and Dr. Jan, for their advice and for letting me use their laboratories and equipment.

I would like to thank my colleagues in Mozambique Dr. Calisto Bias, Dr. Manuel Amane, Mrs. Candida Xavier and extension workers for their collaboration in planning the study and/or participating in soil sampling and analysis.

My special thanks to Mary Johnston and Heui-Park for their support and comments.

I would like to thank my colleagues Guy, Laura, Rowena, Rosalin, Aminata, Tiger, for being available to help me.

I would like to thank my wife Hilaria Saide for her encouragement during my studies and to my son, Mauro Sergio, and to my daughter, Eunice for their understanding and love.

ABSTRACT

This study was conducted to understand soil fertility status, spatial variability of soil properties, and to predict fertilization needs with decision aids. Composite soil samples from 0-15 and 15-30cm were collected in 10 districts located in northern and central Mozambique representing areas of high potential for food production. The sampled locations were georeferenced using Differential Position Systems (DGPS) unit Trimble III. Analysis of various soil's physical, chemical, mineralogical and P sorption capacity were conducted both in Hawaii and in Mozambique. The data analysis were performed using various procedures provided by Statistical Analysis Systems computer package (SAS), GS⁺, Arc Map and Sigma Plot.

Results show that soil fertility is a fundamental problem of food production in Mozambique. The majority of the soils in the study locations are low in effective cation exchange capacity, moderate in organic matter, strongly to moderately acidic, coarse-textured, and moderately weathered.

The X-ray diffractogram indicates that these soils are mostly kaolinitic. The major accessory minerals are gibbsite and goethite. Traces of illite-type clay minerals appeared consistently in the majority of the soils.

In general, these soils can be classified as having low fertility capability, presumably due to weathering stage, low CEC, poor agronomic practices, and in some areas, low pH.

Phosphorus sorption curves show some differences and similarities among soils. The amount of P at 0 P added was below the adequate level in all soils, while the amounts needed to attain 0.2 mg L^{-1} in a soil solution varied considerably because of differences in soil clay mineralogy.

Almost all soils are deficient in N and P. The range of N requirement for maize varies from 20 kg N ha^{-1} to 200 kg N ha^{-1} , and the amount of P requirement ranged from $3.77 \text{ kg P ha}^{-1}$ to $16.9 \text{ kg P ha}^{-1}$. In the platinum region in the central province of Manica, P amendment seems almost impractical because of the high amount needed to correct P deficiency, presumably due to low pH, which is nearly 4.4. The use of acid tolerant crops might be the most appropriate cropping system for those soils.

It appears that K is not deficient possibly because of significant amount of micaceous minerals.

An attempt to estimate economic benefit of fertilizer application indicates substantially low price of the product and high cost of fertilizer. Lack of agricultural policy, poor infrastructure, poor markets for inputs and agricultural products, and lack of financial credit might contribute for low agricultural productivity and hence feasibility of fertilizer use.

Geostatistical analysis of soil properties show spatial dependence with some areas consistently low in exchangeable bases, N and P. However, future sampling could be more efficient if spatial dependence were considered in sample design.

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INTRODUCTION

THE PROBLEM

Mozambique is one of the poorest nations in the world, with an estimated annual Gross Domestic Product (GDP) of US\$171 per capita. The agricultural sector accounts for 40% of the Gross Domestic Product (GDP) and provides employment for over 80% of the economically active population. The country has high agricultural potential. It is estimated that of the total land area of 78.6 million ha, 46% (36 million ha) are considered arable land. Only 9 million hectares of this land are currently in productive use (Dejene and Olivares, 1996).

Agricultural activities are most extensive in central and northern Mozambique. Various studies have emphasized that soil nutrient depletion and soil acidity are major constraints to crop productivity in many areas in Mozambique. Poor agricultural practices, export of nutrients by removal of crop biomass after harvesting, and soil erosion are the most important factors contributing to soil fertility decline (Folmer et al. 1998). It is estimated that over 30,000 ha of agricultural land have the

problem of soil acidity (FAO). Assessment of soil fertility with mathematical models based on land unit and land use systems conducted by Former (1998) indicates that N, P and K are the yield-limiting nutrients for crop production. It is estimated that an annual loss of 32.9 Kg ha⁻¹ of N, 6.4 Kg ha⁻¹ of P and 25 Kg ha⁻¹ of K, result in low crop yield. Although the Folmer et al. (1998) study indicates which areas are likely to have soil fertility problems, it does not provide sufficient information for estimating plant nutrient requirements nor does it provide site-specific recommendations. Currently, efforts to improve food production with fertilizer applications are being carried out by the government and private sector without sufficient knowledge of the type or the amount of fertilizer to apply that might lead to loss of revenue. Progress has been made elsewhere in estimating plant nutrient requirements as demonstrated in work conducted in the Benchmark Soil Project in South America and Puerto Rico (Silva, 1985). However, for the results to be applicable in Mozambique they need to demonstrate the transferability of the methods, which requires understanding the soil fertility problems.

Therefore, a survey of soil fertility status, the prediction of nutrient requirements and liming requirements are important steps in soil nutrient management.

REVIEW OF LITERATURE

STUDY AREAS

The study areas are located in the central and northern regions of Mozambique. According to the Thornthwaite method, the climate of these regions is classified as tropical and sub-tropical. The mean annual rainfall varies from 1,000 mm to 1,400 mm, reaching over 2,000 mm in the higher altitudes. The wet season is from November-December and March-April. The minimum temperature in winter varies from 12°C to 16°C, and the maximum temperature varies from 32°C to 42°C. The altitude of the country varies considerably and influences the climate. The altitude varies from as low as 0 m in the coastal region up to 1300 m in the interior.

The central region has an annual rainfall of 1000 - 1200 mm, during the period between November-March and the mean temperature ranges between 17.5°C and 22.5°C. The risk of erosion is considerable in many areas of central and northern Mozambique.

SOILS

The best agricultural soils are located in central and northern Mozambique. According to the FAO soil legend, the predominant soils in Mozambique are lixisols, leptosols and luvisols in the northern region and arenosols, ferrasols, leptosols and acrisols in the central region with low to moderate fertility. However, caution should be taken in using this soil legend system because of limited access to some regions. Due to civil war, the mapping was based only on satellite imagery data, rather than on field assessment with sample collection and analysis.

AGRICULTURE PRODUCTION AND CROPPING SYSTEMS

In the northern provinces of Nampula and Cabo Delgado, the farms are essentially managed by small-scale farmers. The average area per household rarely exceeds 2.5 ha. In the 70s, small-scale farmers' production in Cabo Delgado, Nampula and Niassa represented 60% of the production of the northern region while in the central and southern northern region small farmers contributed about 52% and 49%, respectively. The private sector contributed 14% of the

total production in the northern, 39% in the center and 41% in the southern regions (Eschwiler, 1986). According to Eschwiler (1986) three factors have resulted in a greater number of small-scale farmers over large-scale farmers:

- a) The geographic position of the region, which made access to British colonies difficult.
- b) A lack of favorable agro-ecological conditions for the main plantation crops such as sugar cane, tea and coffee
- c) A strong resistance to colonial occupation

There are differences in terms of crops and cropping systems among agro-ecological regions. The main food crops cultivated by small-scale farmers in the northern region are cassava, maize, peanuts and beans. Farmers usually match soil with crop production. Soil color and plant type are generally used as indicators of the soil's fertility capability. Crops with specific requirements such as cotton, maize, sorghum and beans are cultivated in clay loam soils, while sandy loam soils are suitable for cassava and cowpea. Nampula and Cabo Delgado accounts over 80% of the total national cotton production area and has been given better technical support by the cotton JVC companies. The central province of Manica has been considered the most

successful agricultural region in Mozambique. International agricultural investment began springing up as its neighbor, Zimbabwe, suffered economic and political problems. The main cereal crops cultivated in small-scale farming in this area are maize, sorghum and millet. Traditionally, maize and cassava are cultivated in mixed cropping or intercropped with cowpeas, peanuts; while millet, sorghum and cotton are cultivated as monocrops.

SOCIO-ECONOMIC FACTORS AS RELATED TO SOIL FERTILITY

POLICY AND ECONOMY

Prior to independence of the country, the private sector contributed the most to agricultural production, accounting for 75% of total food production. After independence, in 1975, agricultural land as well as the importation and distribution of fertilizers and other agricultural inputs came under government control. As the result of a failed nationalization policy, the government was forced to close agricultural production units or to form joint-ventures with the private sector. The impact of such structural reforms has been amply documented in many socio-economic studies. The national per capita food

production has steadily decreased particularly since the 80s, making the country a net importer of food. Research efforts to improve food production have included testing promising crop varieties and using agronomic practices that rely on indigenous knowledge of soil nutrient management or agro-forestry with legumes and other nitrogen-fixing species. Although these strategies are environmentally sound, they are not able to balance the trend of soil fertility decline and the growing demand for food. In recent years, initiatives to improve crop production with the use of fertilizer are being undertaken by the private sector as well as by non-governmental organizations such as Sazakawa Global 2000 and Monsanto. However, lack of information about current soil fertility status prevents growers from making informed decisions about the best soil and nutrient management practices.

SOIL FERTILITY

SOIL PARTICLE SIZE AND SOIL TEXTURE

Soil is composed of solid, liquid, gaseous phases and living organisms. The solid phase consists of organic and inorganic components. The inorganic or mineral component is made up of particles of different sizes that have a profound influence on the soil's physical and chemical properties, and thus on the suitability of the soil as a medium for plant growth (Bohn, 1985). Stickiness and plasticity are two important characteristics of soil physical properties that affect soil management. Soils with a relatively high percentage of coarse fraction are easy to cultivate, whereas soils with a high percentage of clay are sticky and become hard to cultivate when dry (Wild, 1988). The slickness and plasticity not only depend on soil particle size but also on the type of clay minerals, organic coating, and Fe and Al oxides.

Soils with a dominance of clay over sand and silt fractions are described as fine or heavy textured, and soils with a higher quantity of coarse fraction over clay and sand are denoted as light textured. Knowing the fraction of different-sized particles in a soil is

essential for predicting plant nutrient requirements and soil behavior. Attempts have been made to use soil particle-size to predict water-holding capacity, permeability and porosity (Biggar and Taylor, 1956; Tyler, 1992) as well as cation exchange capacity, rheology (Uehara and Gillman, 1981) and organic matter content. Tiessen and Stewart (1983) observed extensive depletion of organic matter associated with particles $> 50 \mu\text{m}$, while organic matter associated with fine clay ($< 2 \mu\text{m}$) showed greater stability. Leinweber and Schulten, (1998) observed that the amount of N increases with a decrease in particle size. The amount and type of clay mineralogy in the soil affects P availability. Measurements of P content in sands, loam and clay loam soils indicate a higher amount of P is sorbed to the soil surface of clay minerals. The P sorption in the soil has been attributed primarily to hydroxyls exposed on the surfaces of minerals and to the phosphate molecule in soil solution (Jackman et al. 1997).

SOIL MINERALOGY

The type of mineralogy predominant in the soil has a profound influence on a soil's physical and chemical properties, making knowledge of soil mineralogy an important part of soil nutrient management. Crystalline and non-crystalline silicate minerals and hydroxides and oxides of Al and Fe, for instance, influence the soil's buffer power and nutrient availability (Prasad and Power, 1997). The strength of electrostatic interaction between soil colloids with ions in solution depends on the type of clay mineral and soil inorganic compounds.

There are at least five groups of clay minerals recognizable by X-ray diffraction techniques: Kaolinite, micas, vermiculite, smectite and chlorite. If judged by their structure, there are two groups of clay minerals, namely, minerals having one layer each of Si-tetrahedra and Al-octahedra (1:1 layer silicates) and minerals having one layer of Al-octahedra and two layers of Si-tetrahedra (2:1 layer silicates). The substitution of Si by Al lowers the positive charge, creating a negative charge. This substitution with ions of similar size is denoted by isomorphous substitution. Soils rich in crystalline oxides such as iron oxides (goethite, hematite, maghemite,

ferrihydrite), aluminum hydroxides and oxyhydroxides have a pH dependent charge and are known as variable charge minerals (Uehara and Gillman, 1981; Prasad and Power, 1997). The composition of these minerals has a profound influence on soil properties.

NUTRIENT AVAILABILITY FOR PLANT GROWTH AND DEVELOPMENT

Sixteen elements are considered essential for plant growth and development. Among them N, P, K, Ca, Mg and S - all classified as macro-nutrients. This distinction is based on the large amount of those nutrients required by plants to complete their cycle of development. For better crop production these elements have to be available in the soil in adequate amounts. Plants exhibit deficiency if one or more elements are below the sufficiency range (Havlin et al. 1999). Predicting soil nutrient deficiency before the plant exhibits symptoms is important to maintain good production. As knowledge of soil and plant relationships accumulates, mathematical models have been adopted as tools to predict crop response aiding in decision-making of management. As far back as the late 1800s and early 1900s, Mitscherlich proposed crop yield as function of factor x

and coefficient C, expressed as $y = Y (1 - e^{-Cx})$. Where y is the yield obtained when x is the amount of the factor present; Y is the maximum yield obtainable if the factor is present in excess and C is a constant (Wild, 1988). However, the model does not describe the complexity of soil and nutrient relationships. Barber, (1984) proposed a mechanistic approach of soil nutrient availability that takes into account the interaction of the soil solid phase with soil solution. He proposed that the availability of some essential elements to growing plants is governed by cation selectivity. Cations with similar valence distribute themselves between exchange sites and the soil solution according to the relative strength of binding of the cation. Other factors that influences nutrient availability include soil water availability, temperature, and soil pH (Prasad, 1997; Wild, 1988). Although other essential elements may be in limiting amounts, there are well-documented studies indicating that N and P are the most limiting factors of food production in many tropical soils.

NITROGEN

Nitrogen is the most abundant element in the atmosphere. However, it is not readily available to most plants. Only legume crops in symbiotic association with rhizobium have the capability to use atmospheric nitrogen through the process termed biological nitrogen fixation.

Nitrogen is almost always deficient in soil, particularly in tropical climates where often rainfall and leaching are extensive. It is estimated that the top 15 cm of soil in a temperate region may contain approximately 0.1 to 0.3% chemically combined nitrogen (Troeh, 1993). Conversely, soils in arid regions have less than 0.1% N in the top 15 cm (Wild, 1988).

Generally the content of nitrogen in surface layers is greater than in sub-surface layers, except when the soil profile contains a horizon of eluviated organic matter, ploughed-in organic matter or a buried A horizon (Wild, 1988).

Nitrogen for non-legume crops in unfertilized soil is largely provided from soil organic N as a result of the mineralization process. Jenny et al. (1985) indicated that climate, vegetation, topography, and parent material are

determining factors of organic matter mineralization, and thus nitrogen availability in the soil. The Nitrogen mineralization, a biologically mediated process, transforms organic nitrogen into inorganic forms, NH_3 or NH_4^+ . Under favorable environmental conditions, much of the NH_4^+ is converted to NO_3^- almost as rapidly as it is formed by nitrifying bacteria in a process called nitrification. On the other hand, NO_3^- can be converted into N_2 , N_2O or NO by denitrification bacteria under anaerobic conditions (Havlin, 1999). Attempts have been made to predict N dynamics in the soil using mathematical models. Some investigators have estimated the gain and loss of N with first order equations:

$$dN/dt = A - rN$$

where the change of N with time dN/dt is equal to N addition (A) minus the amount lost from the system (rN). The integrated form can be expressed as follow:

$$rN = A - (A - rN_0)e^{-rt}$$

Where N is the mass of nitrogen in the soil, A is the annual addition of nitrogen, r is the fraction of nitrogen that is mineralized each year and N_0 is the initial nitrogen content of the soil. In recent cultivated land r is approximately in the range of 0.01 to 0.03. Besides this equation, other more complex equations were devised and

show that the rate of nitrogen mineralization decreases with time, which has been, in part, due to more stable material being formed as the process continues (Wild, 1988).

Temperature has a significant effect on N mineralization. Sierra (2002) devised a model to estimate the daily rate of mineralization and nitrification under fluctuating temperature in a programmable incubator. His results indicate that by increasing the temperature from 20 to 30°C, the N mineralization increased nearly 50%. These results are consistent with those from a study conducted in three locations in Australia. The effect of temperature on mineralization was predicted according a linear regression model $Y = -10.8 + 1.08 * t$, where t is soil temperature. However, these models are considered too simplistic to describe the complex system that is influenced by many factors such as soil pH, vegetation, type, quality of organic matter, and soil moisture which, in turn is influenced by climate.

PHOSPHORUS

Phosphorus (P) is vital in many biological and chemical processes; in fact it has been called the "key of life" (Troeh, 1993). Unlike N and K, P does not occur abundantly in soils, and P deficiencies are widespread in the majority of highly weathered soils (Ultisols and Oxisols) in tropical and subtropical regions (Havlin, 1999; Willet, 1998). It is estimated that the P content of soils varies from nearly 0 to 0.5% with an average of 0.05 (Barber, 1995; Ryan, 1983).

Soil P exists in four categories: (1) Mineral P (2) P as ions and compounds in the soil solution; (3) P adsorbed on the surfaces of inorganic soil constituents and (4) P as constituents of organic matter (Barber, 1995; Novais, 1999).

There are different types of P minerals combined with Ca, Al and Fe. The solubility of such mineral P has a major effect on the availability of P. In alkaline soils, calcium phosphates remain high, while in acid soils iron and aluminum phosphates are dominant (Troeh, 1993; Barber, 1995). There is a body of literature suggesting that Al/Fe oxides are the most important components that influence P

availability. A study conducted by Novais and Kamprath (1978) indicates varying P bonding strength with Al and Fe oxyhydroxide. Soils with high quantities of hematite (Fe_2O_3) sorb less P than do soil rich in goethite (FeOOH), which is due to the lower accessibility of sorption sites on hematite and the greater accessibility to phosphates to individual coordinated OH^- surface groups. The interaction between iron hydroxyl groups with phosphorus is illustrated in figure 2.

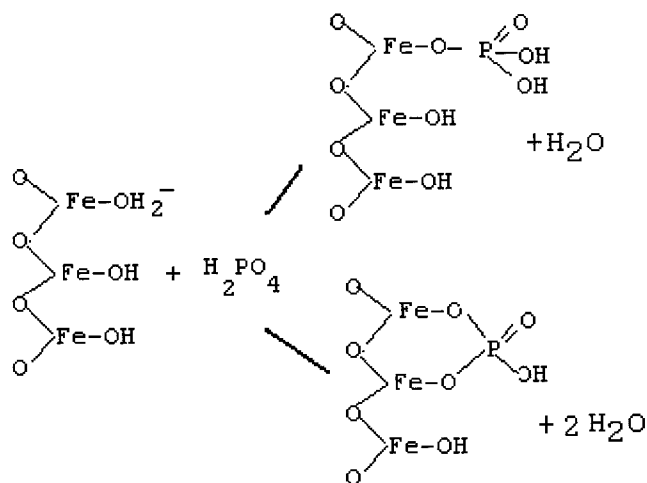


Fig. 1. The reaction of phosphate with a goethite surface. Adapted from David L. Rowell, 1994.

A number of mathematical models were devised to describe the kinetics of P in the soil (Raven, 1993). The most used equations are two. The first is Langmuir represented by:

$$X/m = KCb/(1+KC)$$

Where

C = The equilibrium concentration of adsorbate,

X/m = amount of adsorbed per gram of adsorbent

K = constant related to the bonding energy of the adsorbate to the adsorbent, and

b = the maximum amount of adsorbate that can be adsorbed. This equation often is rearranged to a linear form:

$$C/(x/c) = 1/(kb) + c/b$$

Alternatively, when data fail to fit the Langmuir equation, researchers test the Freundlich equation represented by:

$$X/m = KC^{1/n} \text{ rearranged to a linear form:}$$

$$\text{Log}(x/n) = 1/n \cdot \text{log}c + \text{log}k$$

Where k and n are empirical constants and the remaining parameters are defined as above.

However, some investigators criticized the use of the Freundlich equation because it is an empirical equation

with no physico-chemical meaning of its parameters. The Langmuir equation has similar problems with assumptions that are untenable. Although neither of these models adequately describes such complex soil systems, both have been used effectively to describe phosphate adsorption by a soil. Some of the advantages of the Freundlich equation over the Langmuir equation include (1) two adsorption points are required for the determination of K of Freundlich, while Langmuir needs at least four points to determine k , and (2) transforming the data into log values produces a straight line. On the other hand, a disadvantage of the Freundlich equation is that it does not predict the P requirement for optimum plant growth.

Although P is strongly fixed in the soil, in heavily fertilized farms and where dairy and other animal manures are applied, P becomes a pollutant, posing environmental problems (McDowell, 2001; Pautler, 2000) because an excess of P may cause eutrophication of water bodies, lakes and reservoirs, where water is depleted of the oxygen necessary to sustain aquatic life.

PREDICTING P FERTILIZER REQUIREMENT

There are many ways of predicting P requirements. Traditionally, there has been an empirical approach that takes neither the reactivity of the soil nor the soil buffer coefficient into account. The Phosphorus Decision Support System (PDSS) is an innovative approach that represents an effort to improve the empirical way of estimating P requirements. The model incorporates three components: diagnosis, prediction and economic analysis.

The diagnosis intends to determine whether a problem exists or not. This assessment helps identify the problem so that corrective measures can be taken to minimize loss and damage.

The next step is prediction. If soil P is available in limited amounts, one needs to decide how much P fertilizer is required to obtain a target yield. The data needed to run the prediction are the P critical level, the P existing in the soil, the soil buffer coefficient and the placement factors related as follows:

$$P_{\text{req}} = (P_{\text{critical}} - P_{\text{measured}}) / P_{\text{buffer coefficient}} * \text{Depth}/10 * \text{Placement Factor}$$

Where P_{req} = predicted amount of P required to correct the problem, kg ha^{-1} ; P_{critical} = critical level of P for the intended crop with a particular soil clay content and specific extracting solution. This is the level above which no crop response is expected with the addition of P; P_{measured} = soil P in the field to receive the P fertilizer recommendation, mg kg^{-1} ; $P_{\text{buffer coefficient}}$ = Ratio of increase in extractable P to the amount of applied P fertilizer using the specific extractant, dimensionless; $\text{Depth}/10$ = Depth of application of the fertilizer relative to 10 cm, cm; Placement factor = 1.0 for broadcast, 0.2 for wide band and 0.1 narrow band, where 1 indicates 100% of the row width receives fertilizer, 0.2 indicates 20% of the row width receives fertilizer (15 cm band width for a 75 cm row spacing), and 0.1 which indicates 10% of the row width receives fertilizer. The coefficient of 0.278 accounts for fertilizer efficiency with respect to placement distance from the plant. Table 1 shows the corresponding fractions.

TABLE 1. Corresponding fractions for estimating
 fertilizer efficiency with respect to placement
 distance from the plant.

% of placement distance of 100 cm row width	Corresponding fractions
10%	0.278
20%	0.409

POTASSIUM

Plants require high quantities of K, generally more than soils can supply, except young, relatively less weathered soils that have high K (Barber, 1995; Havlin, 1999). Potassium is second only to N in the quantities required by plants (Havlin, 1999). Potassium is important in many physiological processes such as enzyme activation, water absorption, energy production, translocation of assimilates, N uptake, and protein synthesis. Potassium exists in ionic form either in solution or bound to negative charges on the soil surface through radicals (Havlin, 1999).

Soil K is present in four forms: (1) soil solution K; (2) exchangeable K; (3) non-exchangeable and (4) mineral K (Prasad, 1997; Barber, 1995). The kind of soil minerals and the presence of cations other than K such as Ca^{2+} , Mg^{2+} influence plant K uptake. Potassium in solution has been described by capacity/intensity (Q/I) relations, a concept developed by Beckett, (1964) and Barrow, (1966). The equation is as follows:

$$AR = a_k / (a_{\text{ca+mg}})^{1/2}$$

where K, Ca, and Mg are expressed in moles L^{-1} .

Three important aspects describing the relation of K in the soil solution are (1) intensity, which is the concentration of K in the solution; (2) the soil K buffer capacity, which is the slope of the part of the Q/I curve where $\Delta K = 0$; and the quantity of K which can be readily desorbed, which is obtained by extrapolation of the curve to zero intensity (Rowell, 1988).

Exchangeable K is the fraction that is adsorbed by negatively charged surface minerals.

Soil minerals can contain appreciable K and release it when the K in the soil solution decreases due to either crop removal or leaching.

PREDICTING K FERTILIZER REQUIREMENT

In highly weathered tropical soils with low reserves of feldspar and micaceous minerals or in areas where stover is removed, K may be below the adequate level for crop production. In such conditions, adding K fertilizer may be necessary to ameliorate the K level. The methods widely used in predicting K fertilizer application are Basic Cation Saturation Ratio (BCSR) and Sufficient Level of Available Nutrients (SLAN) (Liebhardt, 1981). The BCSR

concept initially developed by Bear et al., (1945) later modified by Graham (1959) suggests that the optimum soil environment for normal plant growth and development is one that has both the best ratio of basic cations and the best total base saturation. The underlining concept is based on the assumption that the ideal soil is one that has an exchange complex saturated with 65 - 85% Ca, 6 - 12% Mg, 5% K (McClellan, 1977 and Liebhardt, W., 1981) and 20% H (Liebhardt, W., 1981; Malavolta, 1967).

The SLAN concept attempts to determine the sufficient K level. For K the sufficient level has been estimated with the following equation:

$$K_{sl} = 110 + 2.5 * CEC$$

Where K_{sl} = K sufficient level, $mg\ kg^{-1}$ and CEC = cation exchanged capacity, $cmol_c\ kg^{-1}$.

Many authors have stated that the BCSR has serious disadvantages where the use of the K_{sl} equation equally may not be applicable to highly weathered soils of the tropics. Very recently, Yost et al. (2002) proposed a K algorithm that takes into account the plant requirement for K, the soil K reserves, and the reactivity of the soil towards added K. The equation is described as:

$$K_{\text{req.}} \text{ kg ha}^{-1} = (K_{\text{critical}} - K_{\text{field}}) / (BC_K) * BD * (\text{Application depth}/10) * \text{placement Factor} + (\text{Biomass removed} * K_{\text{percentage}}/100)$$

Where

$K_{\text{req.}}$ = K requirement, kg K ha⁻¹;

K_{critical} = critical level of K in the soil, mg kg⁻¹; K_{field}
= Field measured K level, mg kg⁻¹;

BC_K = buffer coefficient for K, for the specific soil,
dimensionless;

B.D. = Bulk density, Application depth = depth of
fertilizer application;

$K_{\text{percentage}}$ = amount of K in the grain or straw or both,
depending on whether one or both are removed as the result
of management, %K.

K CRITICAL LEVEL

By definition, the level above which no response occurs when additional fertilizer is applied is designated as the critical level (Lins, 1989). The K critical level depends on crop, soil extracting solution and cropping system. Fagaria (1984) estimated K critical level of 0.17 cmol_c kg⁻¹ for upland rice, and Adiningsih (1984) estimated 0.19 cmol_c

Kg^{-1} for paddy rice. Gill (1988) defined $0.18 \text{ cmol}_c \text{ Kg}^{-1}$ for soybean, where for cotton the value was between $0.15\text{-}0.25 \text{ cmol}_c \text{ Kg}^{-1}$ (Basset 1963).

K BUFFER CAPACITY

Soil K buffer coefficient is specific for each soil and provides an estimate of the capacity of the soil to supply K to the extractable K pool. It is also used as an indicator of K readily available for plant uptake (Barber, 1995; Khasawneh, 1971; Yost et al., unpublished). There are two ways of determining the K buffer coefficient: laboratory incubation and analysis of field experiment data (Yost et. al., 2000). Literature indicates a field soil buffer coefficient of 0.69 for fine loamy, Typic Paleustult and 0.89 for Very fine, Kaolinitic, Rhodic Kandustox.

The field K buffer coefficient can be computed if the following data are available: (a) soil extractable K, which is determined before the crop is grown and fertilizer K added, mg kg^{-1} ; (b) rates in kg K ha^{-1} at specific depth; and (c) soil extractable K which is measured after the fertilizer is applied, the crop grown and harvested, mg kg^{-1} . The following mathematical equation is proposed for adjustment of BC for K removed by crop.

$$BC_{K_{\text{field}}} = \text{Ext}K_{\text{after}} / (\text{Ext}K_{\text{before}} + K_{\text{added}} + K_{\text{removed}})$$

where

$BC_{K_{\text{field}}}$ = field determined K buffer coefficient; $\text{Ext}K_{\text{before}}$ = extractable K in soil collected before the crop is grown and fertilizer is added, mg kg^{-1} ; $\text{Ext}K_{\text{after}}$ = extractable K in soil collected after harvest, mg kg^{-1} ; K_{added} = amount of fertilizer K added considering the depth of application, mg kg^{-1} ; K_{removed} = amount of K removed in grain and stover.

SOIL ACIDITY

Soil acidity is one of the limiting factors affecting the production and sustainability of crops in many parts of the world. Over 25% of soils in the world are classified as acidic (Havlin, 1999). The distribution of acid soils is closely related to climate and parent material (Rowell, 1988). In humid regions rainfall exceeds evapotranspiration for much of the year. Under these conditions leaching of bases (Ca, Mg and K) occurs; consequently, the soil might become acid (Bohn, 1985). Compounds such as Al and Fe oxides, which are resistant to weathering remain in parent material, and when hydrolysis takes place there is a release of H^+ and a lowering of soil pH.

Chermov conducted comprehensive studies on the properties of acid soils and clays; he observed that hydrogen-saturated soil minerals are highly unstable and, consequently, when they break down, they release Al, Fe and Mg. A number of studies have reported the detrimental effect of Al on many crops (Adams, 1983). High Al concentration reduces root growth. Franco and Munns, (1982) observed that a low level of Al ($>19 \mu\text{M}$) increased total taproot elongation but decreased total root elongation. Conversely, at high Al concentration the taproot also became stunted. Taylor et al. (1998) reported $0.1 \mu\text{M}$ as a toxicity threshold and complete growth inhibition when the Al concentration was higher than $40 \mu\text{M}$. The concentration of Al in soils has been used as an index for predicting soil amendment needs, and provides a better approximation than the use of pH alone (Reeve, 1970; Kamprath, 1970). The best pH of the soil depends, in part, on the crop, soil texture, characteristics of the minerals and organic colloidal fractions.

SOIL NUTRIENT MANAGEMENT DECISION AIDS

Plant growth and development is influenced by many factors. Soil, climate, disease and pests are of significant importance. Because one or more factors can cause some nutrient deficiency symptoms, identifying corrective measures to solve the problem becomes complex. Traditional methods of diagnosing nutrient requirements and development of fertilizer recommendation associate crop response or plant tissue to the soil nutrient availability through multiple factorial trials (Dobermann, et al. 2003). Although this method has been used to assess crop response, regrettably they represent high cost. Now, as the knowledge of soil plant relationships accumulates, it becomes possible to use mathematical models to predict plant response to soil fertility.

The Nutrient Management Support System (NuMaSS Version 2.0), Phosphorus Decision Support Systems (PDSS) and the K model are user-friendly integrated decision aid software, which include diagnosis, prediction and estimates economic benefit based on agro-economic and environmental evaluation. The details of the computation are shown step-

by- step in the section of predictions of soil nutrients requirements.

a) NUTRIENT MANAGEMENT SUPPORT SYSTEMS (NuMaSS)

The NuMaSS algorithms were developed both by the University of North Carolina, the University of Hawaii (Agronomy and Soil Science Department), Cornell University (Crop, Soil and Atmospheric Sciences Department) and Texas A&M (Soil and Crop Science Department). The program has five sections: geography, diagnosis, prediction, economic analyses and results. The data input for diagnosis includes crop management, soil physical and chemical proprieties, and a plant indicator of soil fertility status. There are four important inputs in prediction. The first is the compost, which requires inputs of type and amount or organic amendment. The second is animal manure. It requires input of the characteristics and proprieties of animal manure. The third is plant material properties. The essential features of the program are defined in three models: the nitrogen model, the phosphorus model and economic analysis of production described in the preceding

sections and the acidity module described in the following section.

ACIDITY MODULE

Soil acidity affects crop growth and development in many ways. In general, in most tropical oxisols and ultisols, Al toxicity poses a serious problem to food production. The assumption of the acidity model in NuMass is that highly weathered soils belonging to the Oxisol and Ultisol orders are likely to have soil acidity problems and that the acidity is largely due to toxic Al. The acidity module was developed to aid the user to diagnose and suggest corrective measures to correct the problem of Al or Mn toxicity or Ca and Mg deficiencies (Smyth, 2003). Soil chemical proprieties that have direct influence on soil acidity such as Al saturation, effective cation exchange capacity (ECEC), soil pH in water, and Ca and Mg are given preference in diagnosis. The relative advantage and precision depend mainly on the available data. When the user doesn't provide some information such as Al saturation, the program can use a default mode based on the relationship with soil pH, however the sensitivity of the

diagnosis is adversely affected by the lack of specific information.

The predictions or recommended amount of the amendments are based on comparisons of soil Al saturation with the critical Al saturation of the intended crop; the level above which crop growth and development are affected. The algorithm for lime requirement is based on a modification of the equation of Cochrane et al. (1980) as follows (CRSP staff, 2000):

$$\text{Required CaCO}_3 \text{ in t ha}^{-1} = 1.5 [\text{Al} - (\text{TAS} * \text{ECEC} / 100)]$$

Where,

1.5 = product of a lime factor of 2 equivalent of CaCO₃ for each equivalent of soil exchangeable Al, plus the conversion to field lime requirements at a bulk density of 1.0 and a 0.15 m depth of lime incorporation;

Al = Extractable Al or Al+H with 1 M KCl from the soil, in cmol_c/l or Kg of soil;

TAS = the crop cultivar's critical % Al (or Al + H) saturation of the soil ECEC;

ECEC = the original effective cation exchange capacity of the soil, in cmol_c L⁻¹ or kg of soil.

The model was later refined and three ranges of total Al saturation (TAS) were included as follows (Smyth, 2003):

For TAS ≥ 20%

Required CaCO_3 in $\text{t ha}^{-1} = \text{LF} * [\text{Al} - (\text{TAS} * \text{ECEC} / 100)]$.

If $[\text{ECEC} * (100 / \% \text{ clay})] < \text{or} = 4.5$ then $\text{LF} = 2.5$

If $[\text{ECEC} * (100 / \% \text{ clay})] > 4.5$ then $\text{LF} = 1.3$

For $\text{TAS} < 20\%$ and initial soil % Al saturation $> 20\%$

Required CaCO_3 in $\text{t ha}^{-1} = \text{LF} * [\text{Al} - (\text{TAS} * \text{ECEC} / 100)] + 7.5 [(19 - \text{TAS}) * \text{ECEC} / 100]$

If $(\text{ECEC} * (100 / \% \text{ clay}) < \text{or} = 4.5$ then $\text{LF} = 2.5$

If $[\text{ECEC} * (100 / \% \text{ clay})] > 4.5$ then $\text{LF} = 1.3$

For $\text{TAS} < 20\%$ and initial soil % Al saturation $< 20\%$

Required CaCO_3 in $\text{t ha}^{-1} = 7.5 * [\text{Al} - (\text{TAS} * \text{ECEC} / 100)]$.

Other investigators have proposed the following equations which directly or indirectly include the concept of Al
Coleman et al. (1958):

1) CaCO_3 (ton/ha) = meq Al/100 cm^3

2) CaCO_3 (ton/ha) = 2 - (meq Ca + Mg/100 cm^3)

3) CaCO_3 (ton/ha) = (meq Al/100 $\text{cm}^3 \times 2$) + (2 - meq Ca + Mg/100 cm^3)

4) CaCO_3 (ton/ha) = Y - (meq Ca + Mg/100 cm^3) x f

or

5) meq Al/100 $\text{cm}^3 * f$

where:

Y = 2 for sand soils with less than 1.5% of organic matter

Y = 3 for other soils

f = 1.5 for tolerant crops

f = 2 for not tolerant crops

NITROGEN MODULE

The nitrogen algorithm is intended to assist the user estimate the fertilizer N requirement based on target crop yield. Among other factors, the soil type affects the relative availability of soil N for plant growth as well as the efficiency of the fertilizer source. As related to soil type, two N factors that account for fertilizer efficiency are considered in the algorithm. (a) 0.06 Kg N ha⁻¹ yield in Histosols, and 0.08 Kg N ha⁻¹ yield in all other soils. As indicated in the following equation the amount of N needed to obtain a target yield for crops, except legumes, is a function of soil available N, crop N, manure N and residual N:

$$N_{fert} = [(Y_r * N_{cr}) - ((N_{soil}) + (N_{residue} * C_r) + (N_{manure} * C_m))] / E_f$$

Where, N_{fert} = N fertilizer needed, Y_r = Target dry matter yield, both vegetative and/or reproductive and/or

total dry matter; N_{cr} = Concentration of nitrogen (%N) in vegetative and/or reproductive and/or total dry matter, N_{soil} = Nitrogen absorbed by the crop that is derived from soil organic matter and previous crop residue mineralization, and from atmospheric deposition during growing season; N_r = Nitrogen mineralized from green manures or residues, such as stover or compost that are added to the field; C_r = Proportion of nitrogen mineralized from green manures or residues that are absorbed by the plant; N_{manure} = Nitrogen mineralized from manure; C_m = Proportion of nitrogen mineralized from manure that the crop absorbs; N_{fert} = N fertilizer needed; E_f = Fertilizer efficiency. The crop N needs usually include the following components:

$$\text{Crop N Needs} = Y_r * N_{cr} = Y_g * \%N_g + Y_s * \%N_s$$

Where,

Y_r Total dry matter

N_{cr} Nitrogen concentration in the total plant

Y_g Reproductive yield

$\%N_g$ Nitrogen concentration in the reproductive
portion of the crop

Y_s Vegetative yield

%Ns Nitrogen concentration in the vegetative portion of the plant

The crop available N can be estimated with the following equation:

$$\text{Crop available N} = \text{N}_{\text{Soil}} + \text{N}_{\text{Manure}} + \text{N}_{\text{residue}}$$

The other parameter of the model is fertilizer efficiency (E_f). The N fertilizer efficiency varies considerably depending on soil type, N source, management, and timing. The average aboveground N recover is 40-60%, and for soil-crop-root system varies from 65% and 85%.

In NuMaSS the fertilizer N in the plant was estimated with a linear equation $Y = a + bx$

Where:

Y = fertilizer N in the plant

a = intercept which represents fertilizer in the plant in control plot (theoretically = 0)

b = regression coefficient ($b \cdot 100$ = percent fertilizer N recovery); and

x = rate of applied N.

ECONOMIC ANALYSIS OF PRODUCTION

Economic considerations are essential in developing fertilizer recommendations. Farmers with limited capital need to know whether or not a fertilizer application is profitable. The NuMaSS economics section facilitates the prediction of economic cost and profit. The equation of economic prediction is based on Liebig's classical law of the minimum, which assumes that if the deficient element is supplied, growth will be increased up to the point where the supply of that element is no longer the limiting factor. Nutrient response was described by the linear-plateau production function,

$$Y = \min (a + bx, T).$$

Where Y = Yield;

a = intercept;

b = slope coefficient and

T = optimum yield.

The marginal value product (MVP) is derived by dividing the change in total value of product (TVP) by the change in the value of input, that gives information about how much additional value of output is obtained by each additional amount of the input used- $MVP = \partial TVP / \partial X_1$. The

most profitable level is therefore the level of input where MVP_x is equal to P_x .

Where P = price of the product and

X = quantity. However, a recognized limitation of the model is that nutrients frequently have interactions with each other and effects on growth.

GEOSTATISTICS

SPATIAL VARIABILITY OF SOIL PROPERTIES

Soil properties vary spatially and temporally. Classic statistics deal with spatial variability in the trial site by means of blocking techniques, or by increasing the number of replications. Since classical statistics do not take in account the spatial arrangement, distance and proximity, special techniques were developed (Burgess, 1980). Matheron (1963) developed the concept of regionalized variable. That is, sample values differ less the closer they are to each other (Burgess, 1980; Yost et al. 2002). The exception is when periodic variation in the soil exists (Burgess, 1980). The semivariance is a useful tool in (a) describing spatial variation in the property of interest (Burgess, 1980, Vieira, 1981; Knighton, 1985) and (b) using interpolation of unsampled points (Burgess, 1980). Additional details of semivariance may be obtained from Goovaerts, (1997); Burgess, (1980) and Isaaks, (1989).

There are several models used in describing spatial variability. The most common models are linear, spherical, and exponential. Their characteristics are described below.

Linear model	$\gamma(h) = C_0 + bh$	for $h > 0$
	$= 0$	for $h = 0$
Spherical model	$\gamma(h) = C_0 + C_1 [1.5(h/a) - 0.5(h/a)^3]$	for $h > 0$
	$= C_0 + C_1$	for $h > a$
	$= 0$	for $h \leq 0$
Exponential model	$\gamma(h) = C_0 + C_1 [1 - \exp(-h/a)]$	for $h > 0$
	$= 0$	for $h = 0$

The structure of the model can be described by three main parameters, which are C_0 , $C_0 + C$, and a , defined as nugget variance, sill ($C_0 + C$), and range (or slope in case of linear model), respectively. The nugget variance represents measurement errors or spatial sources of variation at distances smaller than the sampling interval (Burgess, 1980). The sill refers to the maximum semivariance that represents the variability. It represents a value that the variogram approaches when the distance becomes larger and larger. When the sill is exceeded it sometimes indicates that there is a consistent trend or nonstationarity in the data. The range is a parameter of a variogram or

semivariogram model that represents a distance beyond which the samples behave independently (Nielsen, 2003).

The adequacy of the semivariogram model can be estimated by statistical criteria, namely, weighted least-squares and cross validation (Goovaerts, 1997).

KRIGING

Soil sampling of every location is obviously impossible because it will cost too much money and take too much time. The interpolation of unknown points from measured points provides a means to examine spatial processes on an entire surface. This technique is known as kriging, a generic name adopted in recognition of the the pioneering of the work of Daniel Krige (1951). In essence, kriging is the weighted average that takes into account the known spatial dependence expressed by the semivariogram. It appears to provide a more accurate description of spatial structure for studied soil properties than other interpolators as demonstrated in many comparative studies (Kravchenko, 1999).

Mathematically, kriging can be expressed as follows:

$$Z^*(X_0) = \sum \lambda_i Z(X_i)$$

where,

$Z^*(X_0)$ - weighted average of the observed values;

λ_i - weights associated with the data points, which takes in account geographic relationship of the sampled points. Points near (X_0) carry more weight than distant points, points close together tend to have a single weight while lone points carry full weight. Several assumptions are made in kriging a surface. One of the assumptions is stationarity of the data. There are two kinds of stationarity: first order stationarity, which assumes that the mean remains constant regardless the location second order stationarity is second-order stationarity, which means that the covariance exists and it depends only on the lag distance h but not on the sampling position (Nielsen, 2003).

Yost et al. (1982) applied the kriging technique in a study of spatial variability of soil chemical properties of a large area on the island of Hawaii. They found a high range of P sorption (0 to 1800 mg P Kg⁻¹), suggesting that the data were nonstationary. The detrending operation was

tested for improving estimated parameters. Details of principles and statistical background of kriging operation are described in many textbooks (Journel and Huijbregts, 1978; Burgess and Webster, 1980).

The kriging technique appears to have excellent potential in mapping. It can be used to calculate values at unsampled locations, illustrate areas with fertility decline, and low pH; so estimation of the amount of fertilizer or soil amendments can be made for a given region.

In this study, kriging was used to develop a map of soil fertility status, and to map nutrient and amendment requirements at a regional level. The estimation of N requirement for specific location was conducted with NuMaSS. For P and K the prediction was performed with the Phosphorus Decision Support System and K algorithm.

INFORMATION GAPS

1. Information about soil types is available yet much of the information that may be important for soil nutrient management such as soil fertility status, clay mineralogy, and spatial variability of soil properties is still missing.
2. To date, no models have been tested or adapted for local use in Mozambique. Decision-aids are expected to facilitate diagnosing and predicting nutrient requirements.

HYPOTHESES

The following hypotheses are proposed:

- 1 Soil properties vary with time and space and nutrient requirements also change as a result. Site specific nutrient management will provide greater efficiency in fertilizer use.
- 2 Nutrient levels are depleted in many of the soils, often below critical levels, which suggests benefit/cost ratio

analyzes of yield increases and fertilizer applications are greater than 4, suggesting that the practices should be profitable and adoptable.

- 3 INIA's soil analysis methods and results are comparable with results from other laboratories.

RESEARCH OBJECTIVES

- 1 To identify probable nutrient deficiencies or responsive conditions to N, P, K and lime applications.
- 2 To predict approximate fertilizer requirements and estimate the benefit/cost from fertilizer application.
- 3 Relate Mozambique soil laboratory methods and results to those of Hawaii soil analysis data.

MATERIAL AND METHODS

LOCATION SELECTION

Mozambique is divided into ten agro-ecological zones. These zones represent different agricultural potential. The soil sampling plan described here covered three areas situated in central and northern Mozambique (Fig.3). The most important criteria taken into account in selecting locations were (1) high potential for food production; (2) existence of potential users, (3) presence of excellent agricultural support services and (4) accessibility.

The selection of sites for soil sampling in each location was conducted based on existing information (Maps) and extension knowledge of distribution of soil types and zones of agricultural potential. Samples were taken from fields in production but that had not been fertilized in the past four or five years. The sampling scheme followed no regular geometrical pattern. Sixty-four composite samples from 0 to 15-cm and 15 to 30-cm depths were taken using a soil auger. Each sample taken in the northern region (Cabo Delgado and Nampula) was divided in three sub-

samples. One set of samples was left in Nampula, another was at INIA central lab and the other was sent to Hawaii.

The sampled points were recorded using a DGPS unit Trimble GeoExplorer 3. The map below shows the location of sampled points.

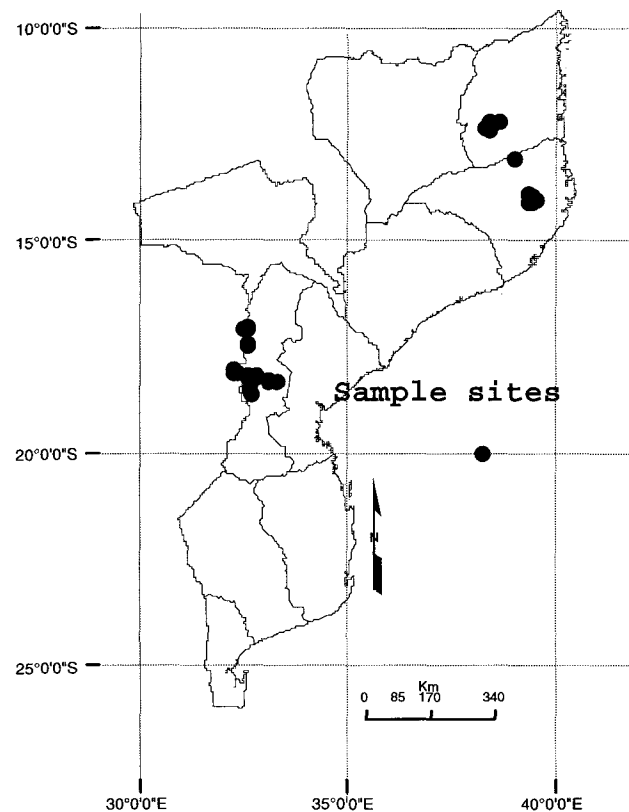


Fig. 2. Sample locations in northern and central Mozambique

LABORATORY ANALYSIS

Soil samples were analyzed for color, particle-size, pH, E_{Ce}, ECEC. The soil air-dry color was determined with Munsell soil color charts outside of the laboratory during the noon hours and the particle-size was determined by the pipette method after destruction of the organic matter with hydrogen peroxide and dispersion with sodium hexametaphosphate (Black, 1965).

The pH was measured with a glass electrode in a 1:1 soil-water suspension and in 1:1 soil-1M KCl suspension. The delta pH was computed as $\text{pH (KCl)} - \text{pH (H}_2\text{O)}$. The electrical conductivity was determined in 1:2.5 soil-water suspension.

The exchangeable bases (Na, Ca, Mg) and Al were extracted with 1M KCl in 1:50 ratio and determined with an atomic absorption spectrophotometer. Potassium, P and micronutrients (Fe, Mn, Zn, Cu and B) were extracted with Mehlich 3 1:10 soil-solution ratio and determined with Inductively Coupled Plasma (ICP). The Effective CEC was computed as the sum of KCl - exchangeable Al and bases. The

percentage of Al saturation was calculated in relation to effective CEC.

The total organic carbon and nitrogen was determined by combustion with LECO CN 2000 automatic analyzer (LECO Corp., St Joseph, MI).

The methods used by INIA's central laboratory were given were the results are discussed.

SOIL MINERALOGY

There are various techniques used in sample preparation for X-ray analyses depending on the purpose of the analyses, equipment available and the research objectives.

In our study the clay minerals were determined with X-Ray diffraction methods. The air dried soil was ground to pass a 2mm sieve, put in 50ml centrifuge tube with approximately 30 mL of water and centrifuged at 10000 rpm to remove soluble salts. The supernatant was discarded. The operation was repeated two times. The clay fraction was obtained by centrifuging at approximately 750 rpm and the supernatant liquid decanted to a separate tube which was centrifuged at 15000 rpm. This operation was repeated until

enough clay was obtained. The concentrated fine clay was placed in glass slide and dried at room temperature for 24 hours. The X-Ray diffraction was conducted with Cu K_{α} radiation to determine the predominant soil minerals.

P SORPTION ISOTHERMS

Phosphorus sorption was determined by Linquist's modified procedure. Three grams of air dried soil passed 2-mm sieve were equilibrated in 50-ml plastic centrifuge tubes with 30 mL background KH_2PO_4 solution containing 0, 2.5, 5, 10 and 20 mg Kg^{-1} P L^{-1} for 6 days. An electrolyte concentration of 0.01 M $CaCl_2$ was selected to represent the soil solution environment of tropical soils with low ion-exchange capacity (Rajan, 1972). The samples were shaken longitudinally in a reciprocal shaker for a 30-minute period twice daily and centrifuged at 15000 Rev./ Min for ten minutes and filtered. Phosphorus in suspension in the supernatant solution was determined with the ammonium molybdo-phosphate-complex method (Olsen and Sommers, 1982).

STATISTICAL ANALYSES

Several statistical analyses were conducted using various procedures provided by the Statistical Analysis Systems computer package (SAS Institute Inc., 1982).

GEOSTATISTICS ANALYSES

Geostatistical analysis was applied for one agro-ecological zone. Different semivariogram models were tested with GS⁺ and Surfer version 8.0 software for describing spatial variability of soil chemical properties. The kriging technique was used to extrapolate to unsampled locations using an ArcMap GIS version 8.2. Predicted soil nutrient requirement at the regional level was conducted using ArcMap GIS.

DIAGNOSIS AND PREDICTION OF SOIL NUTRIENT REQUIREMENTS

The diagnosis and prediction of fertilization needs were estimated with NuMaSS, PDSS and K algorithms.

The data to run the module were given in the section of literature review and soil nutrient management decision-aid.

RELATING SOIL ANALYSES METHODS AND RESULTS BETWEEN
HAWAII AND MOZAMBIQUE LABORATORIES

A comparison between Hawaii soil laboratory methods and results with Mozambique methods and results was conducted. The details of the methods used in each situation are given where the results are discussed.

CHAPTER IV

RESULTS AND DISCUSSION

SOIL CHEMICAL AND PHYSICAL PROPERTIES

SOIL ACIDITY

SOIL pH IN H₂O

The pH varies considerably among sites. The overall mean of 61 samples of topsoil was 5.9, and the range was from 4.4 to 7.8. The median was about 6.0. The standard deviation was 0.53 and the coefficient of variation was 8.9.

Considering a soil with a pH between 5.5 to 5.0 as strongly acidic and below 5.0 extremely acidic (Eschwiler, 1986), 12,9% of the samples were in these categories (Fig. 4, which suggests that these soils are likely to have Al and Mn toxicity or Ca and Mg deficiencies.

Roughly 76% percent of the samples are within adequate levels of pH (5.5 - 6.5), and 11.3% of the samples have pH greater than 6.5.

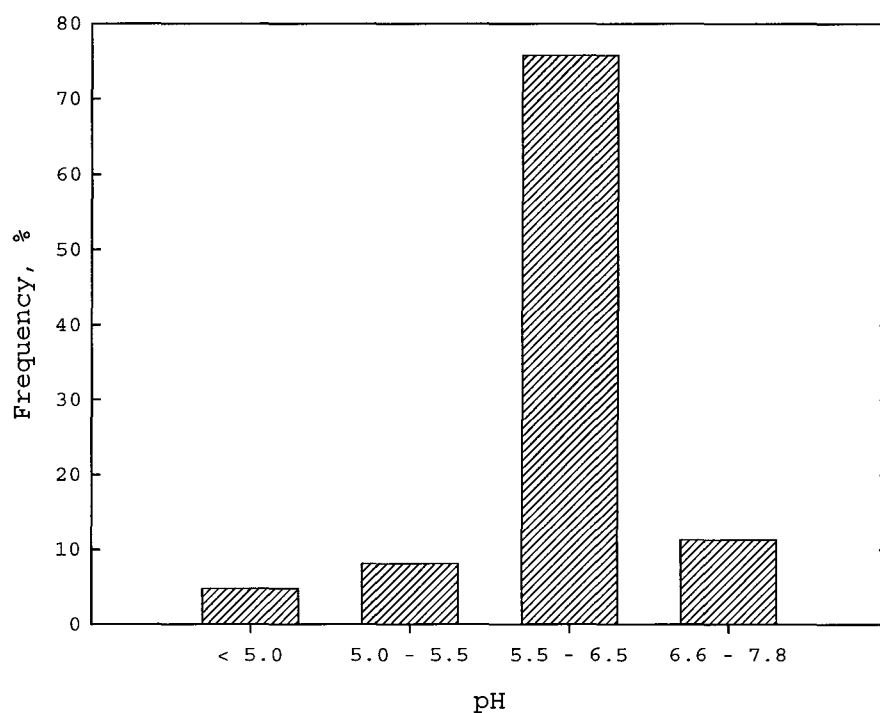


Fig. 3. Frequency of soil pH in topsoil from Mozambique.

A pH in H₂O less than 5.5 will likely require either limestone to lower acidity and improve nutrient availability or the use of an acid tolerant crop. Table 2 indicates levels of pH used in categorizing soil test results in Mozambique; these were used in interpreting the results of soil analysis.

TABLE 2 - INIA's classification of levels of some soil properties

Levels Soil properties	Very low	Low	Medium	High	Very high
Organic matter, %	<1.0	1.0-2.0	2.0-4.0	>4	-
N, %	-	<0.1	0.1-0.2	>0.2	-
P, ppm	-	0-5.0	5.0-10	10 - 15	>15
K , cmol _c Kg ⁻¹					
-Sandy soils, (<10% clay)	<0.05	0.05-0.1	0.1-0.4	0.4-0.7	>0.7
-Clay soils, (>40% clay)	<0.2	0.2-0.4	0.4-1.2	1.2-2.0	>2.0
-Other soils	<0.1	0.1-0.2	0.2-0.4	0.4-0.8	>0.8
Ca, cmol _c Kg ⁻¹					
- Clay soils	<2.0	2.0-5.0	5.0-10.0	10-20	>20
- Sandy soils					
Mg , cmol _c Kg ⁻¹					
- Clay soils	<0.2	0.2-0.5	0.5-1.0	1.0-2.0	>2.0
- Sandy soils	<0.3	0.3-1.0	1.0-3.0	3.0-6.0	>6.0
Na , cmol _c Kg ⁻¹	<0.1	0.1-0.3	0.3-0.7	0.7-2.0	>2.0
C.E.C, pH 7 Cmol _c Kg ⁻¹	<3	3.0-7.5	7.5-15	15-30	>30
Base Saturation, (%)	<20	20-40	40-60	60-80	80-100
pH in H ₂ O		6.1 - 6.5	slightly acid		
<4.5 extremely acid		6.6 - 7.3	neutral		
4.5-4.0 Very strongly acid		7.4 - 7.8	slightly alkaline		
5.6-6.0 acid					

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Comunicação No. 48.

DELTA pH

The delta pH, the difference of pH in KCl and pH in H₂O (pHKCl-pHH₂O) gives information of the net charge or the amount of negative charge on the soil exchange complex (Mekaru, 1971; Uehara, 1981). Negative delta pH indicates a net negative charge on the soil exchange complex or cation exchange capacity; a positive delta pH implies a positive net charge or anion exchange capacity, and a delta pH equal to zero indicate net zero charge (Keng and Uehara, 1971). The pH in KCl in all samples of both topsoil and subsurface layers was lower (<-0.5) than the pH in H₂O, except for one sample of subsurface layer determined by INIA'S method that was slightly positive. In the topsoil, the KCl depressed overall pH by approximately 1.0 unit (Fig. 4a). The ΔpH in this layer ranged from -0.5 to -1.4 pH units (Fig. 4b). According to Uehara and Gillman (1981), this means that these soils are cation exchangers and that when acidic, they are likely to have a high level of extractable Al. However, those soils with less than 10% of clay and high negative delta pH might have appreciable permanent charge minerals.

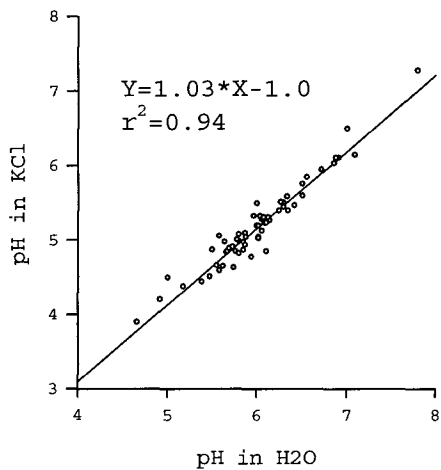


Fig. 4a.

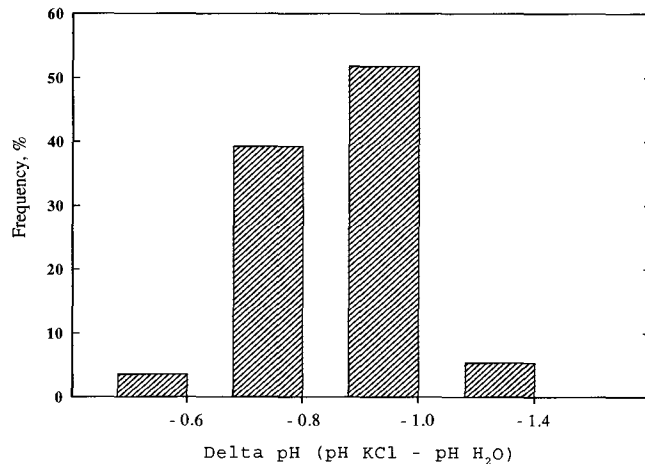


Fig. 4b.

Fig. 4a. and 4b. Relationship of soil pH in H₂O and in 1M KCl for topsoils of Mozambique.

In the subsurface layer (15-30cm), 43.0 % of the samples show higher pH or a lesser degree of acidity than the upper layer. The KCl solution depressed pH roughly one-fold lower than in the topsoil which might be attributed to the predominance of constant surface charge minerals in the subsurface layer than in the surface layer.

Keng and Uehara, (1974) illustrated the effect of pH in variable charge minerals as follows:

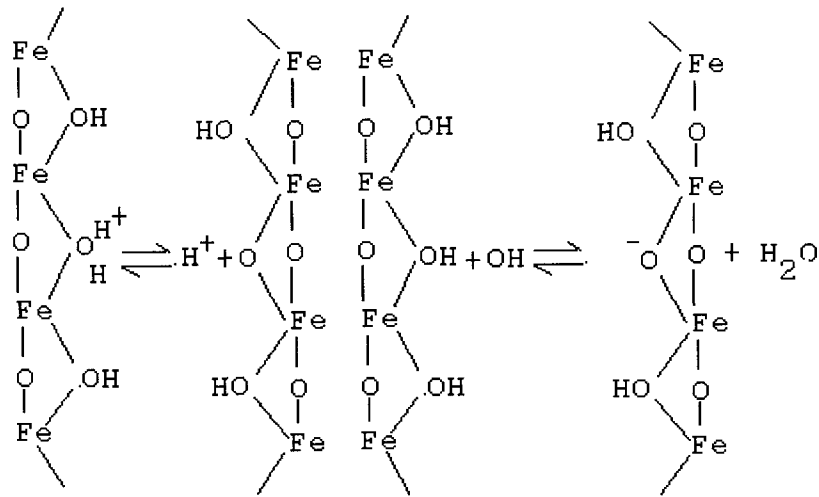


Fig. 5. Origin of surface charge for constant potential colloid (hematite) through protonation and deprotonation of surface hydroxyls.

Source: Keng and Uehara, (1974)

ALUMINUM SATURATION

The percentage of Al saturation of topsoil varies from 1.4% to 58.3%. Fifteen percent of the samples have a percentage of Al saturation greater than 10% and in extremely acidic soils with a pH less than 4.5; the Al saturation was higher than 50%. Most of the soils with appreciable extractable Al were found in high altitude in the interior of the country, over 1,300 meters above sea level.

Assuming 10% of Al saturation as a critical level for most sensitive crops, three soils are likely to have plant growth problems due to Al toxicity or Ca and Mg deficiencies.

Many researchers including Coleman, (1943); Kittrick and Jackson (1965); and Wang et al. (2000) have investigated P reaction with soils, and some have demonstrated that under low pH, oxides and hydroxides of Al and Fe are key factors of P fixation given the high surface area of the colloids.

The relationship between pH in H₂O and KCl-extractable Al of topsoil is best described with a curvilinear regression $(Y=-24.5+175.0/(0.21+x))$. The coefficient of regression indicates that 68% of variation of extractable Al is due to pH. A significant increase of extractable Al was observed when the pH fell below 5.4. These results are in agreement with those found by Kamprath (1970) and Coleman and Thomas, (1967).

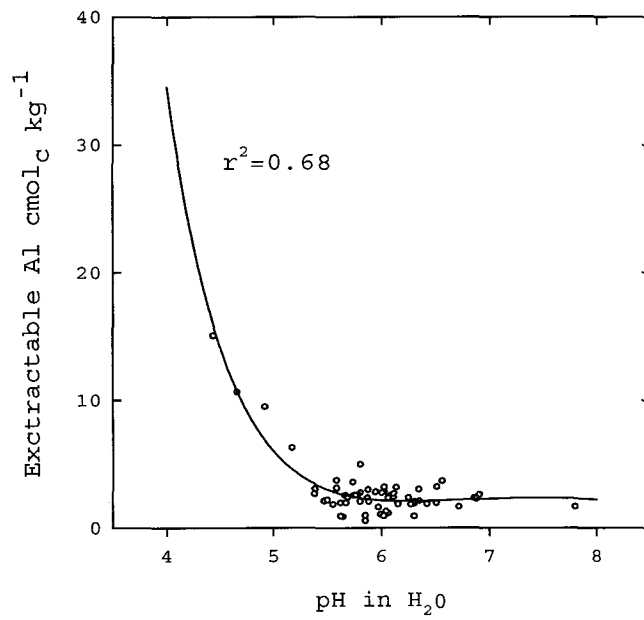


Fig. 6. Relationship between extractable Al and pH for the topsoil of Mozambique.

SOIL ORGANIC MATTER

Soil organic matter has a profound influence on soil chemical and physical properties. It has been used to classify the fertility of a soil as well as its suitability for a given crop (Hester, 1939). Of 61 samples of topsoil in our study of major agricultural regions of Mozambique, the amount of organic matter ranged from 0.4% to 5.7%. The median was 2.1%, and about 47.5% of the samples were below the adequate level. Roughly 46% of the samples were within the medium range (2.0% - 4.0%). Only 5.4% of the samples had 4.0% or more of organic matter (Fig. 7). Therefore, all soils can be classified as mineral soils ($\%OM < 50 \text{ g kg}^{-1}$).

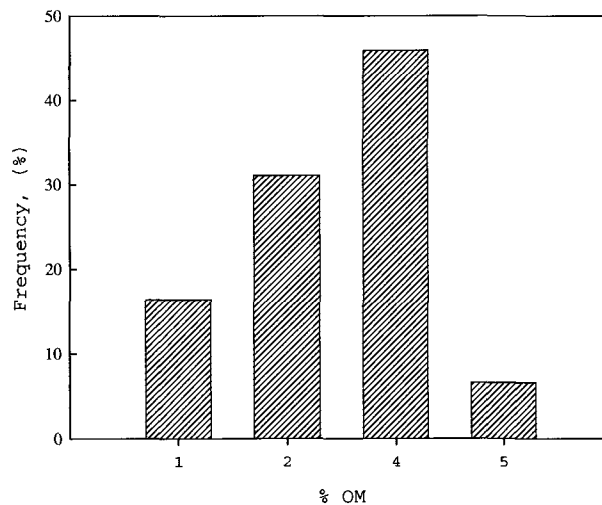
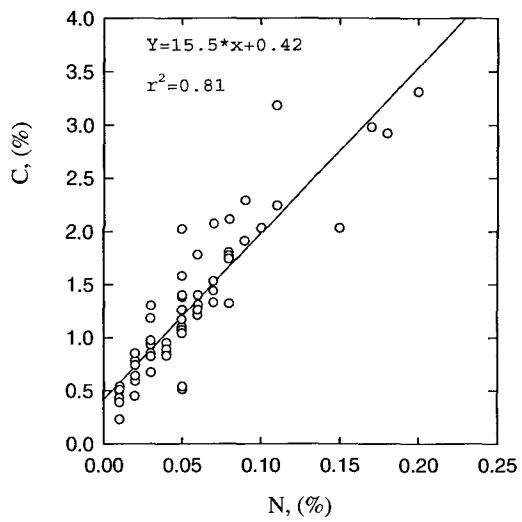


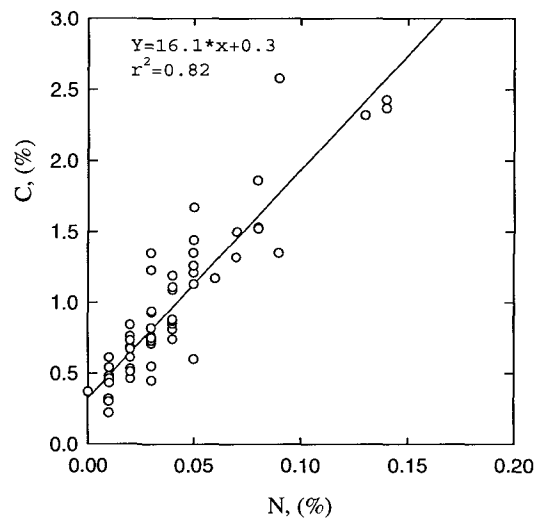
Fig. 7. Frequency of total organic matter in the topsoil samples from Mozambique.

In 88.5% of the topsoil samples, the percentage of OM was higher than in the subsurface samples. The median OM in the subsurface layer was 1.4%, and the maximum value did not exceed 4%, which suggests that, overall, these soils are inherently low in organic matter. There was no statistically significant correlation between organic matter and clay content in either the topsoil or the subsurface layers. The reason for the low correlation between organic matter and clay content in our study might be the nature of soil mineralogy, which is rich in quartz and low in clay minerals.

However, as expected in both topsoil and subsurface layers, there was a positive linear correlation between total carbon and total nitrogen. The correlation coefficients (r) of topsoil and subsurface layers were 0.81 and 0.82 respectively (Fig. 8). These results are in agreement with those obtained by Tan et al. (1970). He showed a positive correlation and approximately the same slope and significant correlation between C and N and as well between N and C, indicating that the value of one or the other can be estimated. However, there is no evidence suggesting that the relationship is valid for other soil types.



(a) Topsoil



(b) Subsurface layer

Fig. 8. Relationship between total carbon and total nitrogen in (a) topsoil and (b) subsurface layers of Mozambique soils.

SOIL PARTICLE SIZE AND TEXTURE

One of the most fundamental soil properties is the distribution of soil particle-size. Knowing particle-size distribution is important in predicting many of the soil physical and chemical properties. In general, results of particle-size analysis conducted at the University of Hawaii indicates that most of the soils are low in clay (Fig. 9). The median clay content was 18.6% and the range was 2.8% to 47.3%. Only 2 samples had 40% or more clay and 17% of the samples had less than 10% clay.

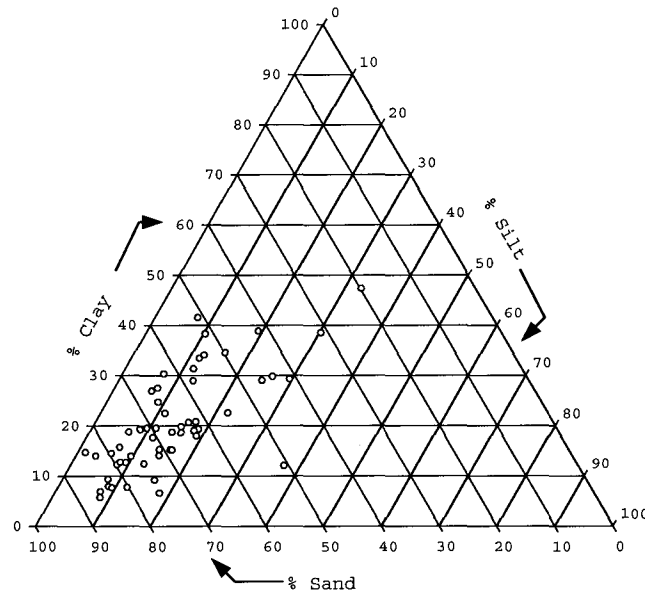


Fig. 9. Topsoil particle-size distribution of Mozambique soils.

In general, the silt/clay ratio was relatively high, which might suggest relatively less weathering of soil materials. Roughly 56% of the samples had a silt/clay ratio greater than 0.5 and only 2 samples had a ratio less than 0.12. Silt/clay ratio greater than 0.12 has been used as an indicator of slightly weathered soils (Ribeiro, 1976). The median of silt/clay fraction ratio was 0.76 and the range was 0.09 to 5.46.

As expected, the topsoil layer had a higher percentage of sand fraction than the subsurface, which might suggest clay eluviation (Whittic, 1959).

X-RAY DIFRACTION PATTERNS

Understanding the soil mineralogy is of particular interest because it provides insights into soil fertility capability. In general, soils that are predominantly Kaolinitic have low CEC, about 10 to 50 mmoles kg^{-1} , low plasticity, and swelling and shrinkage. Soil with a high percentage of smectites have high CEC, high plasticity and high swelling and shrinkage. The X-ray analysis is a widely used method for identifying the type of clay minerals present in the soil. In our study, the X-ray

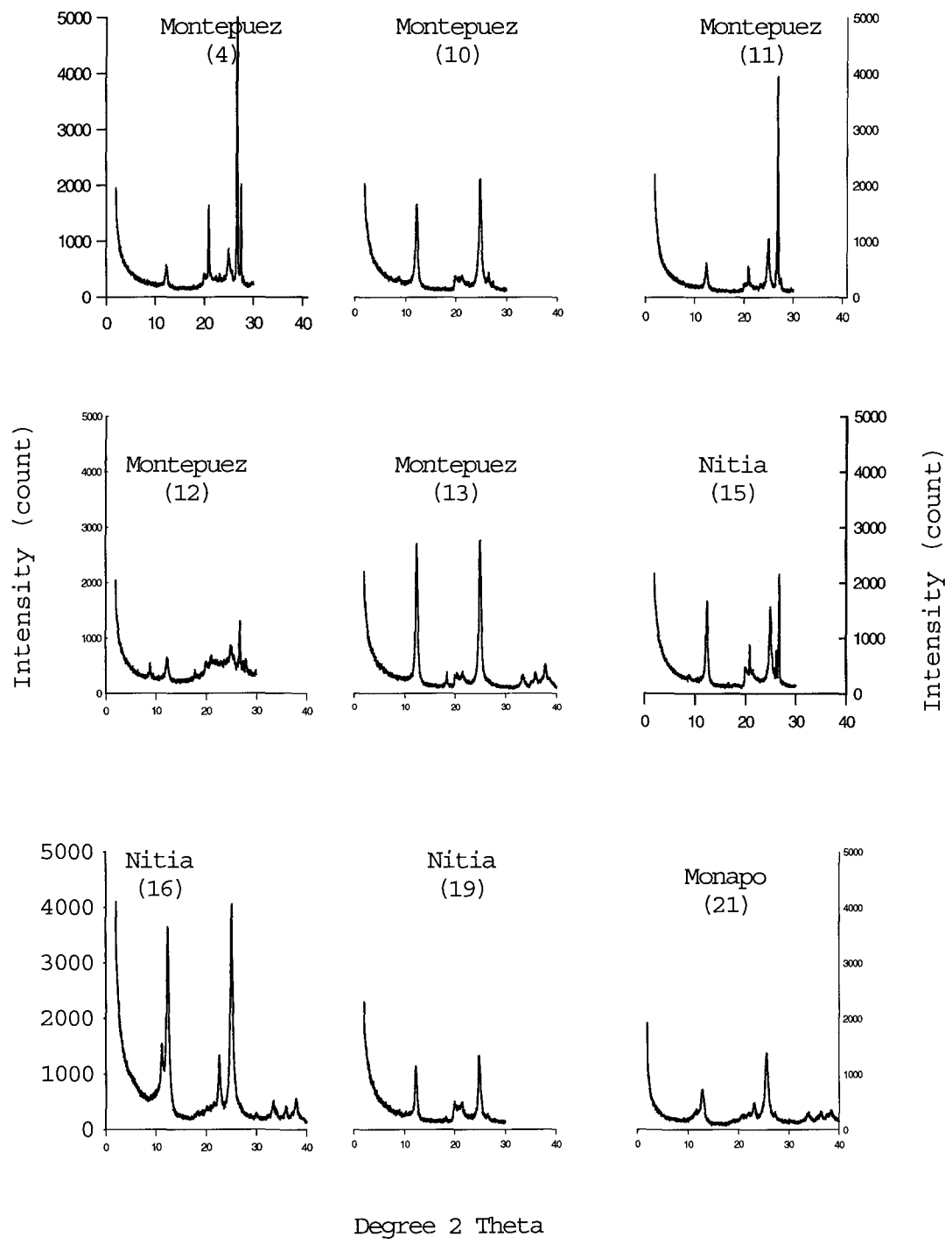


Fig. 10. X-ray deffractograms of selected surface soils (0-15) of Mozambique.

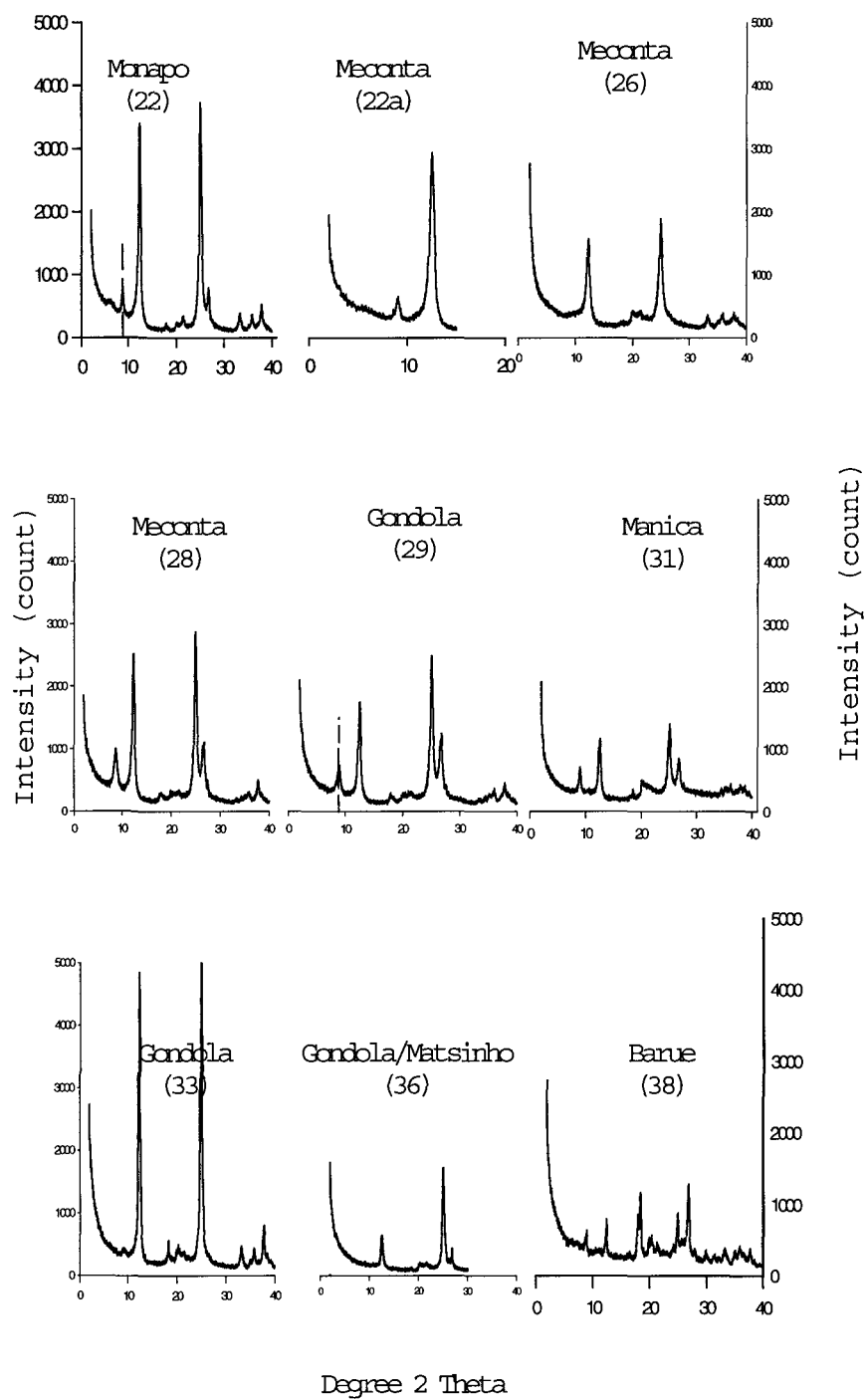


Fig. 10. X-ray deffractograms of selected surface soils (0-15) of Mozambique (continued).

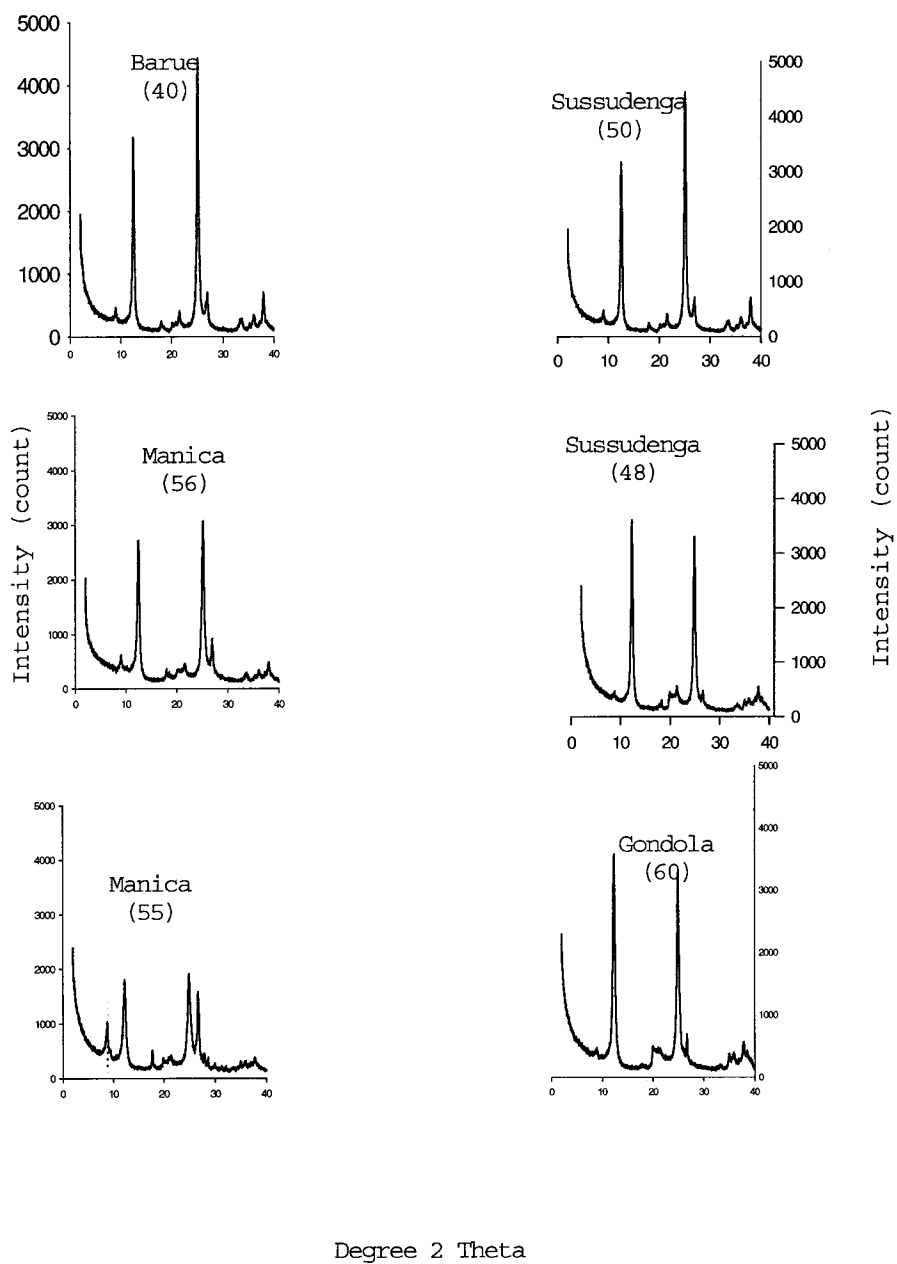


Fig. 10. X-ray deffractograms of selected surface soils (0-15) of Mozambique (continued).

diffraction data were obtained on Siemens D-500 and Scintag PAD V automated diffractometer, at 0.03° ($2^\circ\theta$)/min with Cu $K\alpha$ radiation. Results indicate that the minerals predominant in the soils are similar, consisting mostly of quartz and kaolinite. Figure 10 shows X-ray diffractograms of clay from the surface layers of selected soils. Nearly all of the 28 selected soils show high reflection intensity of the kaolinite group. Unexpectedly, the best peak of this group was obtained with the second order intensity, suggesting that parameter correlation might have occurred. Indeed, there have been attempts to eliminate overlap of the peaks with thermal or, chemical treatments, or instrumental adjustment procedures. However, these processes are often difficult (Moore and Reynolds 1989).

There is little evidence of the presence of smectite clay minerals. An attempt to detect the smectite group was performed by treating the samples with vapor of ethylene glycol-solvated, a procedure that with the exception of high-charge K-saturated minerals (Walker, 1961), allows the expansion of the C space. However, there was weak peak in the range 16.9-17.1 Å (Fig.14-22a), which is suspicious because some samples showed some smectitic properties.

There was a consistent weak peak at 8.77 to 8.92 2°θ, which corresponds to illite. The major peak was found in the Sussudenga district in the central province of Manica (Fig.10-50) and in the Monapo district in the northern province of Nampula (Fig.10-22). The illite peaks are indicated by the dotted lines.

The common accessory minerals in these soils are hydroxides, oxyhydroxides and oxides of Fe and Al. There is evidence of hematite- α -Fe₂O₃ (red color) goethite - α -FeOOH (yellow-brown) and gibbsite - Al(OH)₃, which corresponds to reflection intensities in the regions 2.5-2.3 Å, 4.1-4.9 Å and 4.7-4.85 Å respectively. These species are of significant importance to soil fertility management, particularly because of their strength in P immobilization. One might expect higher P fixation in a soil with goethite

soil than hematite, which has been attributed to more adsorption sites in goethite than in hematite. Fig. 10. shows X-ray diffractograms of selected soils. Other minerals identified with X-ray diffraction are provided in the Appendix II.

NITROGEN AND PHOSPHORUS

It appears that N is the most limiting nutrient in the majority of the soils. The range was 0.01% to 0.2%. The mean was 0.06% and the median was 0.05%. Roughly 89% of the samples had less than 0.1%, a level considered low according INIA's soil fertility capability classification system shown on Table 1. Like N, P is deficient in the majority of soils. The median was 12.7 mg kg⁻¹ and the mean was 17.9 mg kg⁻¹. Assuming the range of 26-35 mg kg⁻¹ P with Mehlich 3 extracting solution measured in the ICP as adequate for most of the crops (Rodriguez et al., 1989), only 13% of samples are within this category. The majority of topsoils shows higher P than the subsurface soils, in which the amount of P dropped considerably.

These results appear to be in agreement with many field surveys that consistently indicate that N and P are the most limiting soil nutrients in Mozambique. In some

areas, in the plateau region, there is substantially low extractable P, which might be associated with high extractable Al. The percentage of extractable Al was greater than 50%.

EFFECTIVE CATION EXCHANGE CAPACITY AND EXCHANGEABLE
BASES

Effective cation exchange capacity (ECEC) is an important indicator of soil fertility capability. Table 3 indicates ECEC and clay content for selected soils. It is recognized, however the limitation of using the FAO soil legend system (Wild, 1988; Eschwiler, 1986) for the classification of soils of Mozambique.

The soils have low ECEC and might be classified as having low to moderate fertility capability. The median of ECEC in all samples was $5.0 \text{ cmol}_c\text{kg}^{-1}$ and the range was from $0.4 \text{ cmol}_c\text{kg}^{-1}$ to $14.5 \text{ cmol}_c\text{kg}^{-1}$. Seventy-five percent of the samples had less than $7.5 \text{ cmol}_c \text{ kg}^{-1}$, the level considered adequate according to INIA's soil fertility capability classification system.

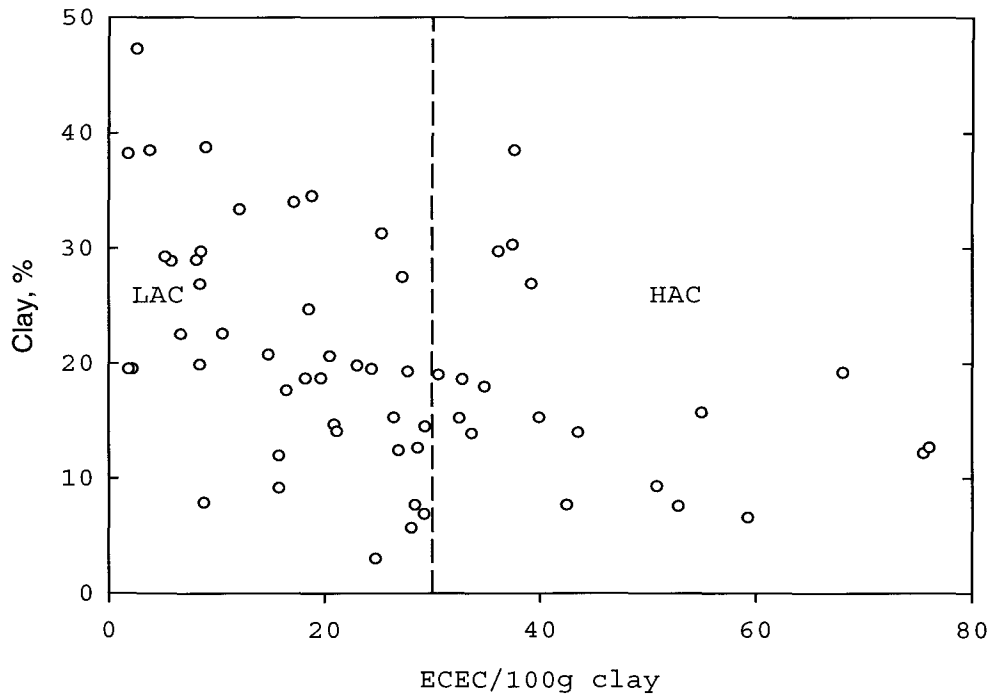
The effective cation exchange capacity per 100 grams of clay ranged from $5.8 \text{ cmol}_c \text{ kg}^{-1}$ to $89.1 \text{ cmol}_c \text{ kg}^{-1}$, and the overall mean was $35.4 \text{ cmol}_c \text{ kg}^{-1}$. The median was $32.9 \text{ cmol}_c \text{ kg}^{-1}$. Only 31% of the samples with an average clay content less than 30% showed a high amount of cation exchange capacity per 100 g clay, which suggests that the majority of the soils have appreciable low clay reactivity.

TABLE 3. Means of selected soil properties of topsoil (0-15).

Soil type	Agro- ecological zones	pH	OM, %	Clay, %	ECEC	ECEC/100 g clay cmol _c kg ⁻¹
Rhodic Ferralsols	R4	5.7	2.5	19.8	5.2	54.4
Lithosols	R10	5.5	1.8	15.2	4.0	26.6
Ferric Luvisols	R4	6.3	2.3	21.3	6.4	37.0
Lithosols - Luvisols	R8	6.3	1.9	21.4	7.0	39.2
Orthic Ferralsols	R7	6.0	2.1	23.3	6.5	33.6

Many of the soils likely to have low reactivity were found to belong to Orthic Ferralsols which are classified as Oxisols according to USDA Soil Taxonomy.

The scatter plot shows the percentage of clay and ECEC/100g clay.



LAC - low activity clay; HAC - high activity clay

Fig. 11. Effective Cation Exchange Capacity/100g clay and clay percentage of surface soils of Mozambique.

In an attempt to evaluate the relationship of ECEC and soil organic matter, pH in H₂O, percentage of clay, percentage of silt and extractable Al, stepwise multiple regression analysis indicates that organic matter pH are statistically significant correlated with ECEC at 0.5 level of probability. Fifty percent of observed variability of ECEC could be explained by e organic matter content, while 64 percent of the variability could be explained by soil pH. Unexpectedly the regressation analysis did not identified clay content and silt as having statistically significant contribution to the variability of ECEC.

MICRONUTRIENTS

In the absence of critical levels of micronutrients for soils of Mozambique, our values have been compared with other studies such as those proposed by Lindsay and Cox (1985) shown in Table 4.

ZINC

The amount of Zn varies from 0.03 mg L⁻¹ to 0.39 mg L⁻¹. The mean was 0.12 mg L⁻¹ and the median was 0.09 mg L⁻¹. Nearly 38 % of the samples had less than 0.09 mg L⁻¹, the

TABLE 4. Summary of soil extracting solutions, shaking time and range of critical levels used in many countries in tropical region.

Micronutrient	Extracting solutions	Soil/Solution Ratio	Time of shaking	Range of critical level
Iron	DTPA, NH ₄ OAC, HCl, NaHCO ₃ , EDTA, NH ₄ F, Na Citrate	1:2 and 1:40	10 minutes to 2 hours	0.4 - 10 mg kg ⁻¹
Manganese	DTPA, NH ₄ OAC, HCl, NaHCO ₃ , EDTA, NH ₄ F, H ₂ SO ₄ , Na Citrate	1:2 and 1:20	5 minutes to 2 hours	1 - 20 mg kg ⁻¹
Zinc	DTPA, NH ₄ OAC, HCl, NaHCO ₃ , EDTA, NH ₄ F, KCl and H ₂ SO ₄	1:2 and 1:20	5 minutes to 3 hours	0.5 - 10 mg kg ⁻¹
Copper	DTPA, NH ₄ OAC, HCl, NaHCO ₃ , EDTA and NH ₄ F.	1:2 and 1:20	5 minutes to 2 hours	0.2 - 10 mg kg ⁻¹
Boron	Ca (H ₂ PO ₄) ₂ .H ₂ O, H ₂ SO ₄ , NH ₄ F and HCl	1:1 and 1:2	5 minutes to 16 hours	0.2 - 2 mg kg ⁻¹
Molybdenum	(NH ₄) ₂ C ₂ O ₄ or hot water	1:1 and 1:10	1 hour to overnight	0.1 - 0.3 mg kg ⁻¹

Source: Lindsay and Cox (1985).

level considered critical with 0.05 M HCl + 0.05 M H₂SO₄ extracting solution. Sommer and John (1947) observed maize zinc-deficiency symptoms in soil with 0.2 mg L⁻¹ to 0.5 mg L⁻¹ with 0.04 M acetic acid extracting solution and from 0.5 mg L⁻¹ to 0.9 mg L⁻¹ with 0.1M HCl. A similar range of Zn critical level was proposed by Lindsay and Cox (1985). However, the Zn critical level depends upon other factors such as the ability of the crop to adsorb and utilize Zn, organic matter content and soil type.

It is generally believed that at low pH, more Zn is available. In our study, however, the amount of Zn extracted with Mehlich 3 did not show a statistically significant decrease with an increase of pH or with the level of organic matter, which might suggest that other factors beyond pH and organic matter control the availability of Zn in these soils.

Studies of crop response to Zn application to different soils of Mozambique are scarce or non-existent. However, studies conducted in a Brazilian red-yellow Oxisol indicate an increase of maize yield of about 21% (494 kg of grain/ha) when 26 kg ha⁻¹ of zinc sulfate was applied (Galvão, 1988). Table 5 shows the means of soil micronutrients (Zn, Mn, Fe, B and Cu) grouped by soil types according to the FAO soil legend map.

TABLE 5. Means of Mehlich 3 extractable micronutrients of topsoils samples of Mozambique soils.

Soil type	Fe	Mn	Zn	Cu	B
	mg kg ⁻¹				
Orthic Ferralsols	88.187a	257.63a	1.392b	1.808b	15.919a
Rhodic Ferralsols	85.890a	192.97a	0.944b	3.126b	15.309a
Lithosols	53.25a	203.36a	1.805ab	12.51a	8.342a
Lithosols-Luvisols	75.36a	229.87a	2.274a	2.049b	8.650a
Ferric Luvisols	90.93a	200.84a	1.209b	2.456b	11.980a
CV(%)	40.00	57.04	63.31	96.5	53.84

Means in the same column followed by the same letter are not significantly different at the 95% probability level by the Waller-Duncan K-ratio t Test mean comparison test.

COPPER

No studies have been conducted in Mozambique that indicate crop response to soil Cu availability. It appears that most of soils have adequate Cu levels. The median of Cu was 3.93 mg kg⁻¹ and the range was 0.97 to 48.0 mg kg⁻¹.

SOIL COLOR

Soil color has been commonly used in soil surveys. Although much has been said about the chances of reproducibility of soil color results, it is still an important tool in predicting soil properties, such as organic matter content, predominance of oxides and sesquioxides of aluminum and iron. The measurement of soil color was based on three measurable attributes, Hue, Value and Chroma, in a system of color notation developed by A. H. Munsell in 1905, from which several revisions were made.

The Hue notation of a color indicates its relation to Red, Yellow, Green, Blue, and Purple; the Value notation indicates its lightness; and the Chroma notation indicates the purity or strength of spectral color (Soil Survey Staff 1951, 1975; Buol, S.W. et al., 1997).

There are substantial differences among samples with regard to air-dried soil color. Fig. 11 shows the frequency distribution of soil color. Wide ranges in color were observed, from 2.5YR (weak-red) to 10YR (dark grayish brown). The majority of the samples (42.4%) have a Hue of 7.5YR. Few samples had a Hue value of 2.5R and 10R (dark grayish brown). It is unclear whether the dark color is due to the clay-organic matter complex or the presence of certain minerals such as titanium-iron compounds, which also generally give a dark color.

In regard to value, roughly 59.3% of the samples have a Value of 4, and 22% of the samples have a Value of 2.5 or 3. Only one sample has a Value of 6.

The majority of samples (81.4%) have Chroma values between 2.5 to 4. Few samples had Chroma values of 5 or higher.

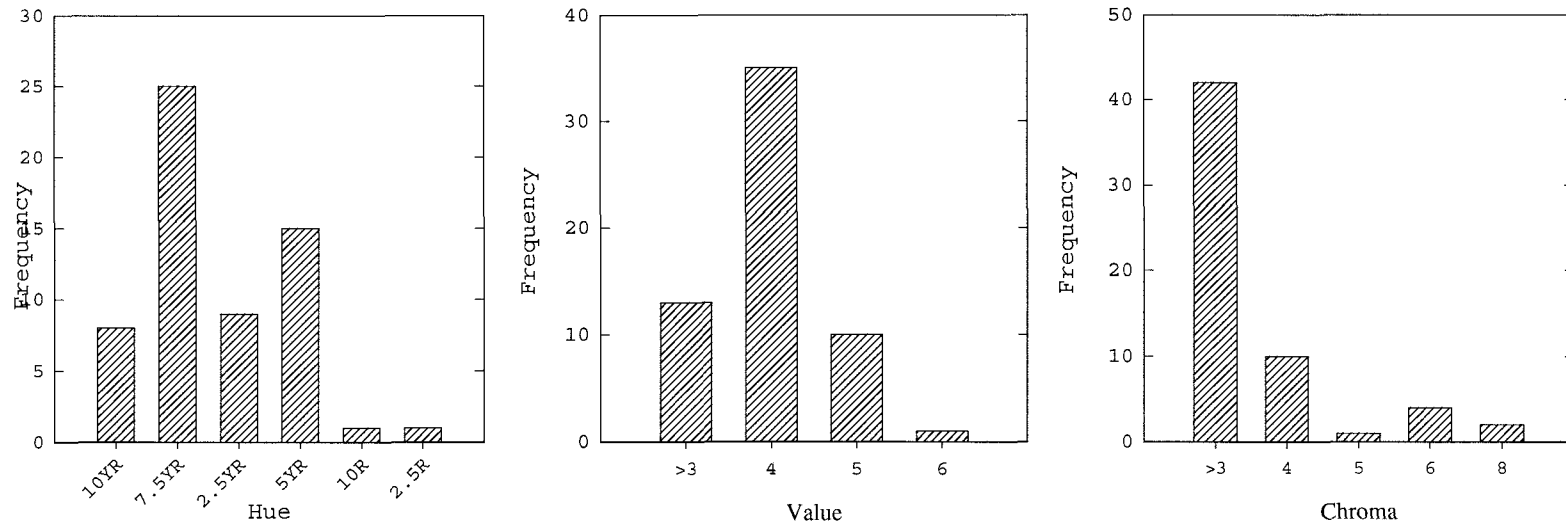


Fig. 12. Frequency distribution of soil color of surface layers of Mozambique Soils.

P SORPTION

The P sorption curve provides useful information for estimating fertilization needs; it gives an idea about the capacity of the soil to supply P to the soil solution. In our study, P sorption analysis was conducted for the surface layers of all soils and for subsurface layers of selected soils. The samples were equilibrated for 6 days. According to Fox and Kamprath, (1970) 6 days is optimum time to attain maximum sorption. A matrix of 0.01 M CaCl₂ was adopted because of an analytical advantage. A clear solution was easily obtained with a matrix of 0.01 M CaCl₂ instead of 0.001 M. Such difference might be explained by the Stern-Gouy model. A high concentration of electrolyte tends to reduce the repulsive force by compressing the double-layer and preventing clay for dispersing (Sparks, D., 1998).

The results of P sorption isotherms for selected soils, having low and moderate P sorption capacity according Juo and Fox 1977 are presented in Fig. 13. All sorption data for individual soils are shown in Appendix III.

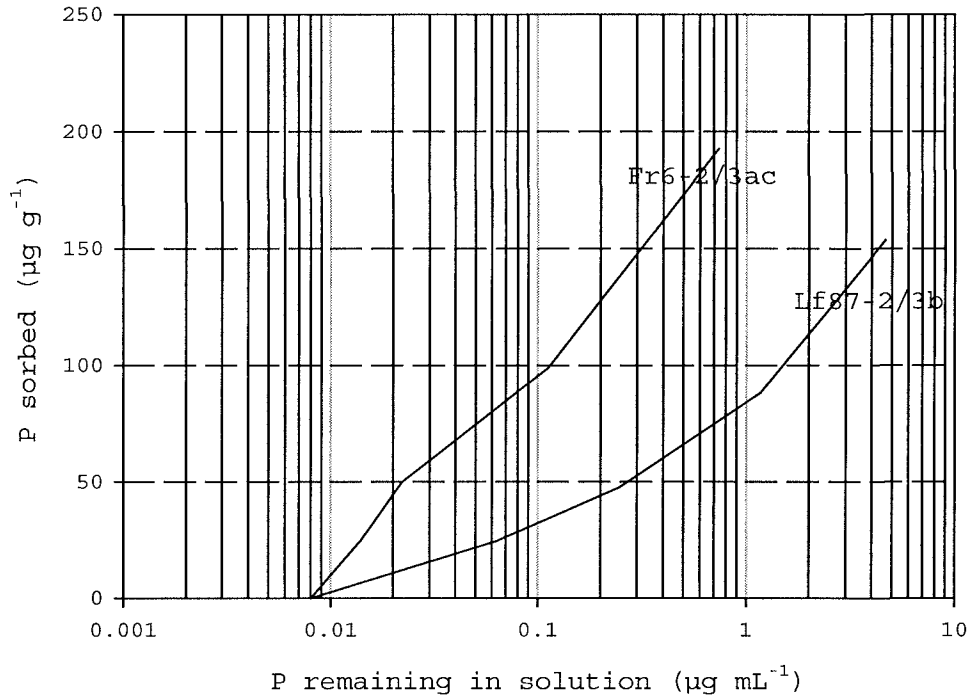


Fig. 13. P sorption curves of Orthic Ferralsols (Fr6-2/3ac) and Ferric Luvisols (Lf87-2/3b) of Mozambique.

In almost all soils, the amounts of P in solution at zero P added are very low, ranging from 0 to 0.042 µg mL⁻¹. It can be seen that available P at zero P added is partially the result of weathering of mineral P and organic matter decomposition, since samples were taken from unfertilized soils. Table 6 shows selected soil properties and equations of sorption capacity of selected soils.

TABLE 6. Adsorption capacity of selected surface soils and their physical and chemical properties.

Soil Type	Silt,	Clay,	Sand,	OM,	pH	%Al	Adsorption equation
	————— (%) —————					Saturation	
Fr6-2/3ac-Orthic Ferralsols (47)	12.9	28.9	58.17	5.38	5.4	10.15	$Y=41.213\ln(x)+200.17;$ $R^2 = 0.99$
Lf87 -2/3b-Ferric luvisols (44)	11.2	19.5	68.34	1.26	6.9	3.92	$Y=-10.475x^2+78.535x+$ $14.613; R^2 = 0.97$

It appears that for the Ferric luvisols, the relationship between P remaining in solution and P sorbed by the soil is well described by the second order polynomial regression, while for the other soil the logarithmic relationship seems to give the best fit. The r^2 was highly significant for both soils.

Many factors are involved in the interaction between P and soil such as soil mineralogy, chemistry, biology, and management (Fox, 1982). An attempt to evaluate the relationship of soil properties and P sorption curves by stepwise regression indicates no statistically significant effect of clay content and organic matter on P sorption. Jackman, et al. (1997), studying P sorption by selected Hawaiian soils found that clay content and chemical properties alone did not provide a good estimate of P sorption capacity. Indeed, in noncalcareous, nonallophanic soils the P adsorption has been associated with oxides and hydroxides of iron and aluminium present (Juo and Fox 1977) especially as goethite.

With the exception of a few samples, generally soils with a sand fraction over 80% show low buffer capacity. These soils might need more applications of P because of the low capacity of the soil to sorb P. On other hand, the

2.5YR and 10YR (Yellowish-red) soils, classified as Oxisols, have high P retention capacity, possibly because of the high reactivity of soil colloids. According to Juo and Fox (1977) these soils can be classified as having low (10-100 μ g P/g soil) to medium (100-500 μ g P/g soil) P sorption capacity.

The majority of the soils with high reactivity were found in the Monapo district, in the northern province of Nampula and also in Manica, Sussudenga and Barue districts in the central province of Manica. This is especially true when we compare the X-ray diffractograms. The samples taken in the Barue district show more prominent reflection intensity in the regions 2.5-2.3 \AA (Fig. 10-40). In those soils, the amount of P needed to obtain 0.2 mg mL⁻¹ in the soil solution, the level considered adequate for normal plant growth (Fox and Kamprath, 1970) was very high, and ranged from approximately 200 mg mL⁻¹ up to 400 mg mL⁻¹, which clearly indicates high sorption capacity. The sorption capacity of a soil has a positive value since the soil can continue to supply P to soil solution as plant takes up P from the soil solution (Uehara and Gillman, 1981), however to the growers it represents great investment in P fertilizer to bring P to the adequate level.

In some respects it appears that there is no consistent difference among soils belonging to the Orthic Ferralsols (Fo75-2/3ab), Lithossols- Luvisols (I-L-1b), and Lithosols (I-Bc-V) (Fig. 14). Those soils show very little slope. The obvious reasons can be either the inefficient FAO soil legend in clustering these soils or the low reactivity of the clay mineral constituent. In contrast, significant differences can be observed between the Rhodic Ferrasols (Fr6-2/3ac) and Ferric Luvisols (Lf87-2/3b).

Fox and Searle (1978) ranked the adsorption capacity of the soils in the following order: quartz=aluminum-free organic matter<2:1 clay<1:1 clay<crystalline oxides of iron and aluminum< amorphous oxides of aluminum and iron.

Although P sorption curves provides insight into the ability of soil to sorbe P, for practical use of P sorption isotherms for determining fertilization requirements, it needs to be correlated with a soil P extraction method.

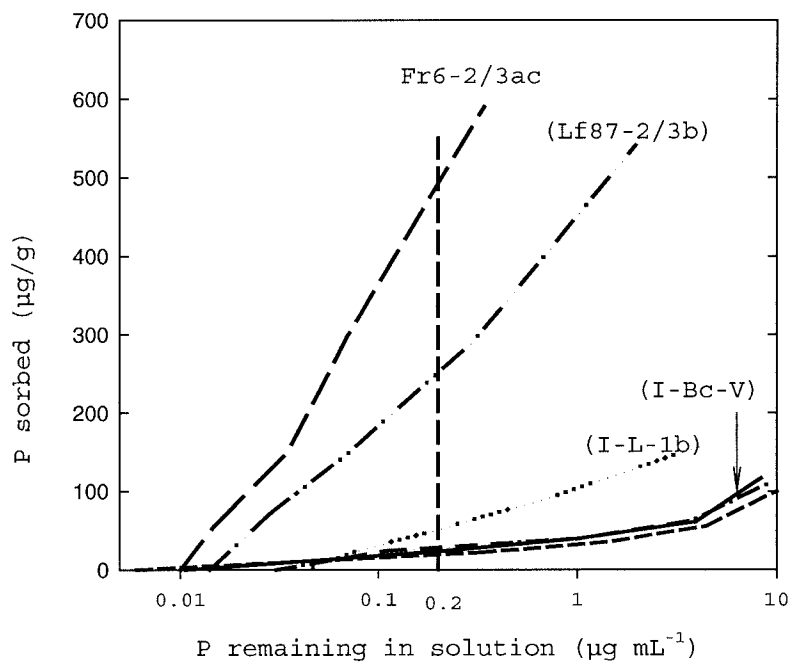


Fig. 14. P sorption curves of selected soils of Mozambique

PREDICTION OF N REQUIREMENTS

Plant N availability depends on N input or gain and output or loss from the soil. Various mathematical models with different degrees of sophistication were devised to predict N balance based on this principle. The NuMaSS prediction of the N requirement is based on a modified version of the Stanford equation, which follows the same principle.

Details of the components of the model are given in the section on materials and methods. A review of the model is as follows:

$$N_{\text{fert}} = (Y_r * N_{\text{cr}}) - [N_{\text{soil}} + (N_{\text{green manure}} * C_{\text{gm}}) + (N_{\text{manure}} * C_{\text{m}})] / E_{\text{f}}$$

where:

N_{fert} = N fertilizer needed

Y_r = dry matter yield, both vegetative and/or reproductive and/or total dry matter;

N_{cr} = concentration of nitrogen %N in vegetative and/or reproductive and/or total dry matter

N_{soil} = Nitrogen from soil organic matter and previous crop residue mineralization and from soil atmospheric deposition during growing season;

$N_{\text{green manure}}$ = Nitrogen mineralized from green manure
in current growing season

C_{gm} = Proportion of N mineralized from green manure in
current growing season;

C_{m} = Proportion of nitrogen mineralized from manure
that plant absorbs;

E_{f} = Fertilizer efficiency

Studies of nitrogen balance in Mozambique are scarce.
Some of the inputs of the model in predicting N
requirements were assumed from field studies conducted
elsewhere. Table 7 shows the corresponding coefficients for
the NuMaSS prediction of N requirements.

TABLE 7. Corresponding factors for predicting N requirements

Crop Variable Relations	Corresponding NuMaSS N Coefficients
Aboveground N accumulation vs. grain yield	Y*Nc for targeted yields
Apparent N recovery vs. applied fertilizer N	Ngm
Apparent N recovery vs. applied green manure N	Cgm

Source: P. Luna et al., 1991.

The first component ($Y_r * N_{cr}$) in the algorithm estimates the amount of N recovered by the crop. Literature indicates an aboveground N accumulation per unit of grain yield ranging from 0.017 to 0.027 kg N kg⁻¹ grain yield for maize. In our computation the aboveground N accumulation was calculated using the following regression equation derived from a field experiment in an Oxisol in the wet-dry climatic region.

$$Y = 9.6 + 0.024 * X$$

Where

Y = total above ground N accumulation in kg ha⁻¹ ;

X = grain yield in kg ha⁻¹

Experimental data suggest that the average grain yield in Mozambique in a rainfed condition rarely exceeds 4.0 ton ha⁻¹. This yield corresponds to approximately 106 kg N ha⁻¹. Tables 8 and 9 show the average yield in experimental plots in the northern region and in demonstration plots in the central region.

TABLE 8. Maize mean grain yield (kg ha⁻¹) for the northern region - Experimental data.

Nitrogen Kg/ha	P applied, Kg P ₂ O ₅ ha ⁻¹			Mean (N)
	0	40	80	
0	2930	2920	3280	3040
60	2740	3240	4060	3350
120	3230	4280	5050	4190
180	3130	4430	4330	3960
Mean (P)	3010	3720	4180	3640

Source: J. Rendle, P. Woodhouse, 1985.

TABLE 9. Mean grain yield (kg ha⁻¹) in maize Fertilized demonstration plot (100 kg ha⁻¹ NPK 12:24:12 + 100 kg ha⁻¹ Urea).

Variety	Mean
Manica	2867.2
Sc 513	3087.5
Sussuma	2152.7

Source: Manica Extension Services

The second component of the model is N existing in the soil derived from previous fertilization, atmospheric deposition and/or from mineralization of crop residue. This component was obtained from soil laboratory analysis and converted to a soil basis.

The third component is N_{residue}, which was calculated by multiplying the mineralization rate and the percentage soil nitrogen content.

Mineralized nitrogen [(Kg N ha⁻¹ crop⁻¹) = (BD*15*10⁵*% Soil N*mineralization rate)]/Crop Yr⁻¹

We assumed that the average mineralization rate in tropical soils which ranges from 2% to 6% was 4%. The values 15 and 10⁵ were used to convert kg ha⁻¹ for 15 cm depth.

The fourth component is animal manure. This component was not included in the computation since farmers don't apply manure.

The last component is fertilizer N efficiency (E_f), which corresponded to the slope of the relationship between apparent N recovered and applied N. Results of the field experiment from West Africa and South America indicated a range of N recovery of 41% to 47% (Luna et al. 2001). In our computation, we assumed 41% fertilizer efficiency

because high risk of production and loss of N by leaching as the majority of soils are within the coarse-textured category.

Using the above components the calculation indicated a range of fertilization needs from 20 kg N ha⁻¹ to 200 Kg N ha⁻¹ for a maize crop.

Studies conducted in India indicated aboveground N accumulation as a function of sorghum grain yield described with the following equation:

$$Y=18.2+0.025*X$$

Comparison of predicted N requirements with current fertilization rates on maize suggests that the algorithm gives a fairly good approximation. However, a few soils appear to have adequate N for maize. About 32.2% of the samples need supplementary N if Sorghum is grown. The estimated amount ranged from 34.0 to 81.59 Kg ha⁻¹ or 52.3 to 125.4 Kg of urea. It is uncommon to have sufficient N in the soils given the fact that soil samples were taken from unfertilized lands and generally turnover of organic material is very low due to poor management of the biomass.

PREDICTION OF P REQUIREMENTS

The P requirement was predicted with the Phosphorus Decision Support System (PDSS) algorithm, which represents an effort to reduce the resources with a traditional approach of estimation of fertilize needs. The algorithm was tested in different soils and crops in Thailand and Western Africa with a reasonable degree of correlation between predicted yield and actual yield (P. Luna et al. 1991). The algorithm uses a critical level of P, soil P, P buffer coefficient, depth of fertilizer application and a placement factor. The P buffer coefficient and the P critical level used in the computation of the P requirement were estimated with segmented linear regression equation developed by Shuai et al., (2003) as follows:

$$P_{\text{buffer coefficient}} = 0.867 - 0.215 * \% \text{clay}$$

$$P_{\text{critical level}} = 28.336 - 0.633 * \% \text{clay}$$

Many investigators have suggested the use of clay percentage in predicting soil buffer capacity (Lins and Cox, 1985).

The placement factor of 0.287 was considered in the computation to adjust for the P plant uptake efficiency. This is a empirical value obtained from field experiments

and corresponds to the amount of P needed to provide equivalent nutrient uptake for band placement of P at 10% of row width. It is based on the de Wit theory of fertilizer placement represented by the following equation:

$$U_r/U_b = (X_r/X_b)^{0.44}$$

Where

U_r and U_b are the relative nutrient uptake from the row and the broadcast; X_r and X_b are the relative widths of the localized placement with respect to the row width. If the fertilizer is placed 100%, 20%, and 10% of the row width, it would give 1.0, 0.409 and 0.278 efficiency. That is, if the P application is made to 20cm out of the 100cm row width, then 0.409 as much fertilizer is needed to provide an equivalent nutrient uptake.

Combining all factors in the equation of P requirement, gives a wide range of P amendment needed to attain an adequate amount of P, varying from 3.77 kg P ha⁻¹ to 16.9 kg P ha⁻¹. That corresponds to a range of 18 kg ha⁻¹ to 80.5 kg of Diammonium Phosphate ha⁻¹ or roughly 8 kg ha⁻¹ to 37 kg ha⁻¹ of concentrated superphosphate, which appears to be a reasonable estimate for DAP. J. Rendle and P. Woodhouse, (1985) observed an average yield of 5050 kg ha⁻¹ of maize when fertilized with both 80.0 kg DAP ha⁻¹ and 120 Kg N ha⁻¹.

Although the levels of extractable P vary significantly among soils, the analysis of variance (ANOVA) indicates no statistically significant differences at the 95% level of probability, which is acceptable because for a study in a large area, spatial variability generally causes high coefficients of variation. Therefore, the GLM program might not be adequate for assessing differences among locations.

Bhatti et al. (1991) studying spatial correlation from a yield experiment observed that classical statistical analysis was unable to detect crop response to fertilization needs in soil known to be deficient in nutrients. The failure to detect crop response differences was due to the presence of trends and experimental error, a problem that was treated with geostatistical techniques.

TABLE 10. Predicted fertilizer requirements (kg DAP
 ha⁻¹) for selected soils

Soil type	% of clay	P Buffer coefficient	P requirement (kg DAP ha ⁻¹)
Rhodic Ferralsols	19.8	0.46	59.3
Lithosols	15.2	0.56	65.2
Ferric Luvisols	20.4	0.45	63.8
Lithosols-Luvisols	20.0	0.46	53.2
Orthic Ferralsols	21.8	0.42	63.0
CV, %			16.0

DAP - Diamoniumphosphate

PREDICTION OF K REQUIREMENTS

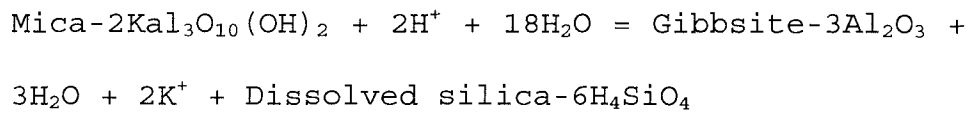
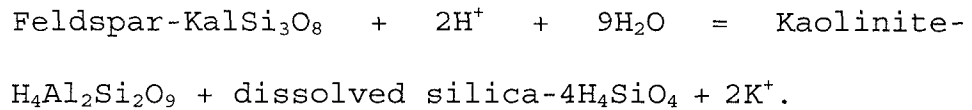
Currently there are no K fertilizer recommendations in Mozambique. Most of the studies have dealt with N and P and more recently with Mo. Regretably, none of the investigations have studied in detail soil properties as related to fertilization efficiency.

In our computation of the K requirement, we used the K algorithm developed by Yost et al. (2002) through field studies. The algorithm uses the reactivity of clay expressed as the soil buffer coefficient, critical level, placement factor, and biomass management. The biomass management factor is taken into account because the K level is significantly affected if biomass is removed. Details of the input needed to run the prediction are shown in the section on soil nutrient management.

Results of the computation show that the majority of the soils are not K deficient, except four samples that show little difference between soil K and the K critical level. Addition of K to those soils might be necessary to offset crop removal.

The high K level observed in the majority of the soils seems to agree with the mineralogical study. The X-ray

diffraction patterns show a strong reflection intensity at 10 Å, suggesting presence of micaceous minerals that might release K as weathering processes take place. Garrels and Christ (1965) described the process as follows:



It is important, however, to recognize the limitations involved in using the critical level developed elsewhere in computing fertilization needs for Mozambican soils because other factors that influences fertilizer recovery might be different.

PREDICTION OF LIMING REQUIREMENT

Liming a soil is a common practice to raise a soil pH to a level adequate for normal plant growth and development. In general, soil with a pH less than 5.5 needs either liming material to reduce Al toxicity and improve nutrient availability, or the use of Al tolerant crops.

Results of a soil pH survey indicated that 11.5 % of the samples were within the strongly acid or extremely acid category, with pH varying from 4.8 to 5.5. It is almost certain that those soils with a pH less than 5.2 are likely to have problem with Al toxicity or Ca and Mg deficiencies (Kamprath and Foy, 1985). In this situation, the use of acid tolerant crops or soil amendments are an imperative need for better crop production.

For predicting liming requirement we used a modified equation of Cochrane et al. (1980). The equation estimates the amount of lime needed to only neutralize the quantity of exchangeable acidity that exceeds the intended crop's tolerance level.

The components of the equation are given in the acidity model in the literature review. The simplified form is as follows:

$$\text{Required CaCO}_3 \text{ in ton. ha}^{-1} = 1.3 [\text{Al} - (\text{TAS} \cdot \text{ECEC}/100)]$$

Where,

1.3 = product of a lime factor of 2 equivalents of CaCO₃ for each equivalent of soil exchangeable Al, plus the conversion to field lime requirements at a bulk density of 1.0 and a 0.15 m depth of lime incorporation;

Al = extractable Al or Al + H obtained with a 1 M KCl extraction of the soil, in cmol_c L⁻¹ or Kg of soil;

TAS = the crop cultivar's critical % Al (or Al + H) saturation of the soil ECEC;

ECEC = the original effective cation exchange capacity of the soil, in cmol_c L⁻¹ or kg of soil.

$$\text{The ECEC} = \sum_{i=1}^n (\text{Ca} + \text{Mg} + \text{K} + \text{Na} + \text{Al})$$

Plant species and varieties within species differ significantly in their tolerance to Al toxicity.

Field studies in Puerto Rico and Brazil indicate a substantial increase of yield when the soil with Al saturation greater than 35% was limed. Under similar growing condition sorghum has the same requirements, although a high pH is more beneficial. Results of the computation indicate an average liming requirement of 635 Kg CaCO₃ ha⁻¹ for maize and about 1300 Kg CaCO₃ ha⁻¹ for sorghum. According to our data, the areas with major amendment needs are located in Barue and most likely Sussudenga in the central province of Manica, probably due to high rainfall and a high degree of weathering.

Other areas with potential acidity problems include Nitia and Montepuez in the northern provinces. Those areas represent over 80% of national cotton production, while Manica might have the potential for cotton production.

Cotton is a very sensitive crop to acidity. Optimum growth was obtained when the Al saturation was near zero (Kamprath, 1970; Alley, 1981). Assuming TAS of 5% and initial soil percentage Al saturation of specific location gave liming requirement ranging from 2.35 to 5.23 ton ha⁻¹.

The soil properties and liming requirements for the major crops are shown in the Table 11.

Table 11. Liming requirements for main crops and soil properties of selected soils from Mozambique.

Soil type	Crop	Crop TAS, %	Soil pH	ECEC, cmol _c kg ⁻¹	Clay, %	Al sat.	Lime requ., tones ha ⁻¹
Manica (Ferric Luvisols)	Maize	35%	4.6	3.69	19.7	54.24	0.635
	Sorghum	15%	-	-	-	-	1.3
Nitia - I-L-1b - Lithosols	Cotton	5%	5.2	10.86	3.02	22.96	1.68
Montepuez - Fo75-2/3ab - Orthic Ferralsols	Cotton	5%	5.1	3.65	12.2	2.89	2.36
Gondola - Fr6-2/3ac Rhodic- Ferralsols	Cotton	5%	4.9	3.67	6.9	20.68	2.84
Barue - Fr6-2/3ac Rhodic Ferralsols	Cotton	5%	4.6	2.69	19.7	54.19	2.93
Gondola - Fr6-2/3ac Rhodic Ferralsols	Cotton	5%	5.1	4.62	6.74	20.61	4.04

Other investigators have proposed other methods for predicting liming requirements, which directly or indirectly include the concept of exchangeable Al developed by Coleman et al. (1958). Nonetheless, one equation might provide a better estimate than another, depending on the soil type and other physical and chemical soil properties.

ECONOMIC ANALYSIS OF PRODUCTION

In developing countries where the growers have limited resources and the prices of agriculture products are low, fertilizer use represents a high cost. Therefore, selection of type and amount of fertilizer should be made on economic grounds. The economic analysis algorithm in NuMaSS considers the cost and revenues associated with fertilizer applications based on the linear response plateau model, which implies that the level of revenue is determined by the deficient nutrient. The survey of soil fertility described in this thesis clearly indicates that N and P are below adequate levels. In selecting fertilizer grade for these soils it is wise to chose urea (45%) and superphosphate or urea and diammonium phosphate as a supplementary source of N and P instead of the widely used 12:24:12. The common practice of blanket application of 12:24:12 might represent monetary loss if soils are not K deficient. Regretably, farmers are constrained by the available fertilizer in the market and the insufficient information on soil nutrient status and crop requirements makes it difficult for them to make informed decisions.

In our study an attempt was made to estimate the economic benefit of fertilizer application. Data for the

evaluation of expected returns such as the value of the product was obtained from the local market and extension services. The price of fertilizer was provided by the retailers. Other costs were estimated based on the author's knowledge of the production system. However, because of the absence of yield response to predicted fertilizer needs we were unable to estimate the revenue due to fertilizer application. Nonetheless, we provide estimated variable inputs in Mozambique (Table 12).

Under the current farmers' production environment, due to lack of an agricultural policy, fertilizer cost is high and farm gate prices are low resulting in low profit. Cotton, on the other hand, may be profitable.

TABLE 12. Estimated cost of fertilizer application

Variable Inputs (Xi)	Maize MZM	Cotton MZM	Sorghum MZM
Labor,	3,000,000	3,000,000	3,000,000
Seed	300,000	100,000	100,000
Fertilizer :			
- Urea (16,000/kg)	2,500,000	2,000,000	2,000,000
- Superphosphate (19,500/kg)	720,000	720,000	720,000
Total cost	6,520,000	3,822,000	5,820,000

\$1 = 19000 MZM

GEOSTATISTICS

SPATIAL VARIABILITY OF SOIL PROPERTIES

Geostatistical techniques are very useful tools for describing spatial and temporal variability of natural phenomena. They have been widely used in quantifying, mapping and managing spatial variations of soil fertility. In our study, the application of geostatistics aimed to analyze spatial variability of selected soil properties for the surface layer, and to estimate the amount of fertilizer and amendment needed in a given region, within which the level of a given nutrient is spatially dependent.

The first step in analyzing spatial variability of soil properties is calculating the average, variance and variation coefficients in order to decide whether or not the data need to be transformed. Results indicate a high coefficient of variation for Al, Ca, Mg, K, C and N, and a low coefficient for pH. All parameters are kurtotic and asymmetric. Al and P show higher skewness (Table 13).

The obvious reasons for non-normal distribution might be attributed to the differences in soil type, cropping

TABLE 13. Statistical parameters of variograms of selected soil properties

Soil properties	Mean	St. Dev.	Median cmol _c kg ⁻¹	CV, %	Skewness	Kurtosis
pH	5.78	0.30	0.35	6.03	-0.52	1.20
Al, cmol _c kg ⁻¹	0.32	0.19	0.19	61.02	2.53	8.57
Ca, cmol _c kg ⁻¹	3.04	1.44	1.44	47.42	1.24	3.69
Mg, cmol _c kg ⁻¹	0.74	0.36	0.36	48.04	0.90	0.66
K, cmol _c kg ⁻¹	0.47	0.20	0.20	43.12	0.80	0.85
P, mg L ⁻¹	1.77	1.45	1.45	81.95	1.37	1.17
C, %	1.48	0.76	0.76	51.55	0.99	0.55
N, %	0.07	0.75	0.05	70.95	1.45	1.21

systems and rainfall. A log transformation of the data was performed before the data were analyzed statistically.

Figure 15 shows variograms of selected soil chemical properties.

Different models were tested. The best fit of semivariogram was obtained with a spherical model. The r^2 was highly significant (>95%) (Table 14). The nugget variance for all samples ranged from 0 to 0.13. The magnesium showed the highest nugget.

The range varies from 2500 to 7350 m, with C and N showing the highest values and Mg the lowest, which is normal because different soil properties are involved in different physical and chemical processes.

Given a limited number of points, the kriging of the surface was not carried out.

TABLE 14. Geostatistical parameters for selected soil properties

Soil properties	Nugget Variance	Sill (C+Co)	Range (Ao) [m]	Spatial dependence [C/(C +Co)]	r ²
pH	0	0.06	5250	1.10	1.10
Al	0	0.06	5260	1.03	1.03
Ca	0.01	3.81	6800	0.95	0.95
Mg	0.13	0.69	2500	0.97	0.97
K	0.03	0.03	6000	0.98	0.98
P	0	5.5	4500	1.03	1.03
C	0	1.74	7350	0.98	0.98
N	0.01	5.3	7000	0.97	0.97

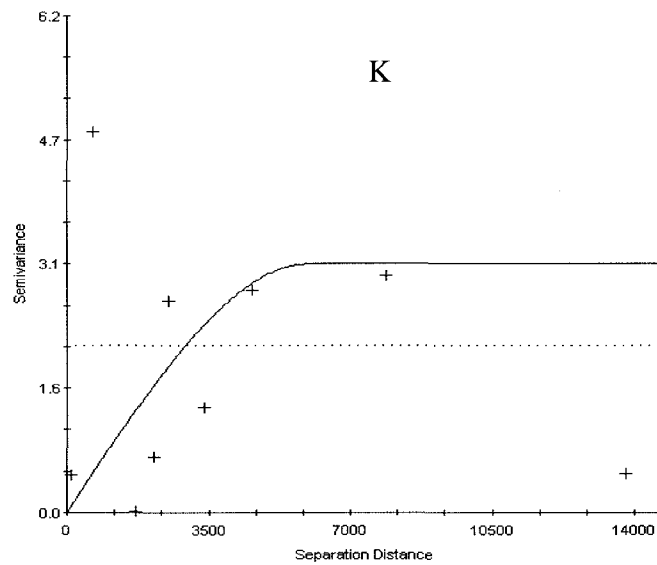
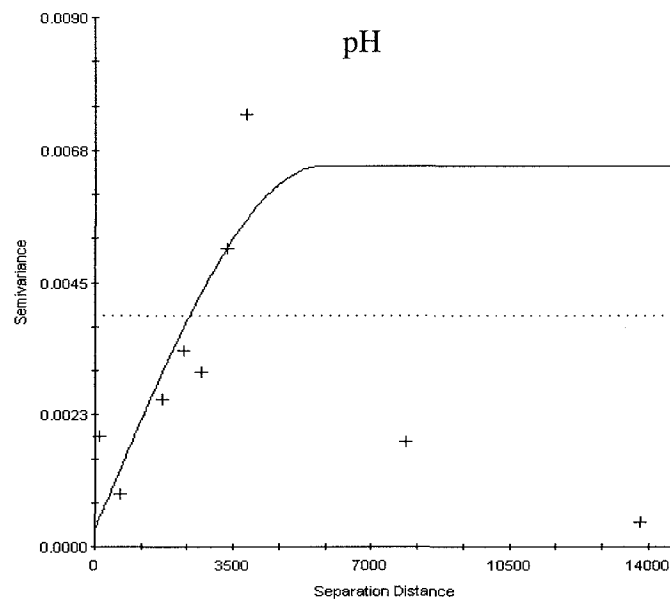


Fig. 15. Spatial variability of some soil chemical properties of surface layer of selected soils of Mozambique.

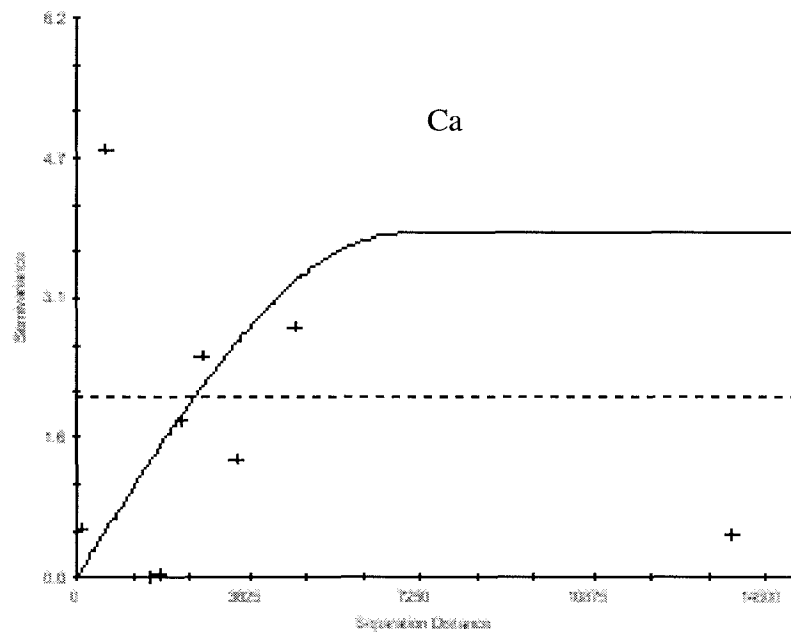


Fig. 15. Spatial variability of some soil chemical properties of surface layer of selected soils of Mozambique. (continued)

PREDICTION OF NUTRIENT REQUIREMENTS AT A REGIONAL LEVEL

One of the features of GIS is its ability to estimate areas, volumes and to visualize spatial parameters.

How much fertilizer or amendments are needed for a given region, and what rate of application is of interest to agricultural managers and other decision makers.

Knowing the spatial variability of the relevant parameters helps one predict the estimated amount of fertilizer or amendment needed for the entire region. In this study, the amount of N, P and amendment to correct soil nutrient deficiencies or increase soil pH to an adequate level was predicted with N, P, and acidity algorithms. Geospatial techniques were applied to predict the spatial variability of fertilization needs of a limited area. A limited area was selected due to great distance between sites of this survey (Fig. 16). The estimated fertilization needed was computed by buffering the zones according to the variogram range and then assuming the same within this region.

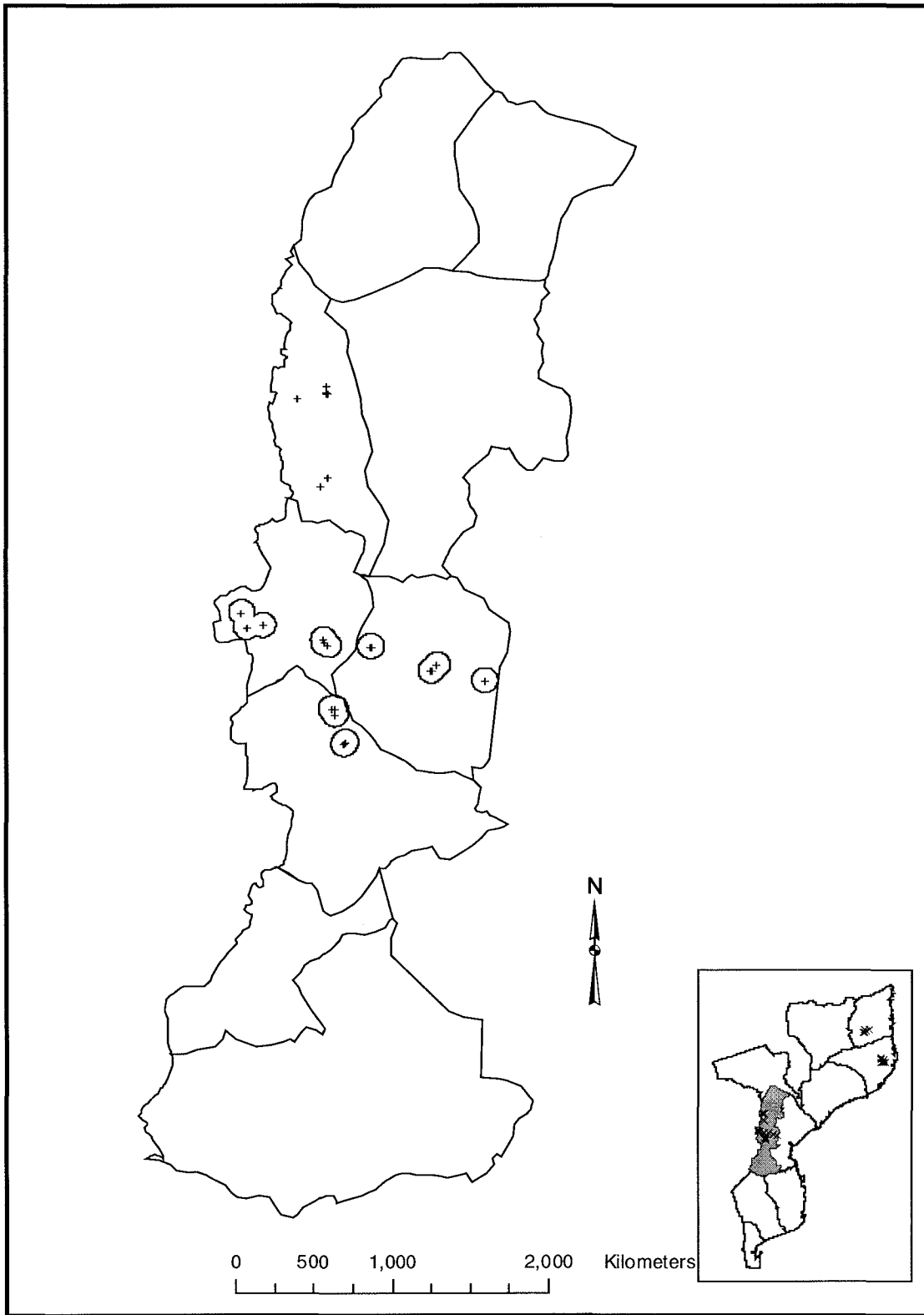


Fig. 16 Sample locations with 6.1 km buffer showing area of extrapolation.

For overlapped areas the amount of fertilizer or amendment was computed by averaging the fertilization needs as follows:

$$\text{Average N}_{\text{req.}} \text{ (kg ha}^{-1}\text{)} = A_i * \sum(X_i) / n$$

Where

A_i = partial area, ha⁻¹

X_i = Site-specific N requirement, kg ha⁻¹

n = Number of points within the area

The amount of fertilizer for the sampled region can then be computed by multiplying the total area with the average fertilizer or amendment needs. Further studies should consider small sampling intervals in order to better estimate regional requirements. The table below indicates the average amount of fertilizer required for selected locations in the central region of Mozambique, where minimally sufficient samples were taken for geostatistical techniques to be applied.

It is important to note that the area might include non-agricultural land.

TABLE 16. Estimated amount of N and P for a crop of maize required for sample locations with fertilizer needs

Location	Total Area	N Req. (Kg ha ⁻¹)	Total N (ton)	P Req. (Kg ha ⁻¹)	Total P (ton)
Manica	11309	119	1340	33	375
Sussudenga	11309	122	1383	63	708
Gondola I	11309	155	1758	63	710
Inchope	11309	92	1035	60	679
Gondola II	11309	60	679	40	448
Vanduzi	11309	176	1992	57	640

RELATING UH AND INIA CENTRAL LABORATORY ANALYSIS

Comparison of soil testing results is a common method used among soil-testing laboratories analysis in order to improve soil analysis procedures. There have been no recent comparative studies of soil-testing methods to determine whether INIA's central laboratory results are correlated with those of other soil-testing laboratories. The primary objective of the comparison of INIA's central laboratory and Hawaii results was to identify 1) whether the methods are the same and if so; 2) whether the results using the same methods are the same. Such comparisons can both lead to a useful discussion of methods and when the methods are the same, a comparison of technique.

Single-factor correlation is a widely used technique to test whether the results are the same. Six soil properties that were analyzed by the same method were analyzed with regression. The results for the topsoil layer are presented in Table 17.

TABLE 17. Relationship between Hawaii and INIA's
central laboratory results of selected
soil properties

Soil properties	n	Correlation coefficient
pH [†]	55	0.86
Texture		
Sand	55	0.95
Silt	55	0.63
Clay	55	0.93
Total C	57	0.95
Total N	56	0.88
EC [†]	62	Ns
ECEC ^{††}	62	ns

[†] pH and EC were measured in 1:2.5 soil/water ratio in INIA's central laboratory and 1:1 in Hawaii laboratory;

^{††} ECEC measured with ammonium acetate buffered at pH 7.0 by INIA's central laboratory and with Mehlich 3 and 1M KCl solutions by Hawaii laboratory.

Ns - not significant.

SOIL pH

The results of soil pH can be misleading if the testing method is not known. Some laboratories determine pH in saturated past, others use 1:1 soil: water ratio and others measure pH in a more diluted mixture of 1:2.5 soil:water. The method used by INIA was 1:2.5 soil:water ratio while the laboratory in Hawaii used a 1:1 soil:water ratio. Nonetheless, there were no significant differences between INIA central laboratory data and Hawaii's data. The slope was close to 1.0. The coefficient of correlation was significantly positive ($r = 0.84$). Similar results were obtained in five selected soils measured in Hawaii in both 1:1 and 1:2.5 soil:water ratio. The t test indicates no statistically significant differences at 95% probability between pH in 1:1 and 1:2.5 soil:water ratio, which suggests that the dilution effect was not significant in these soils.

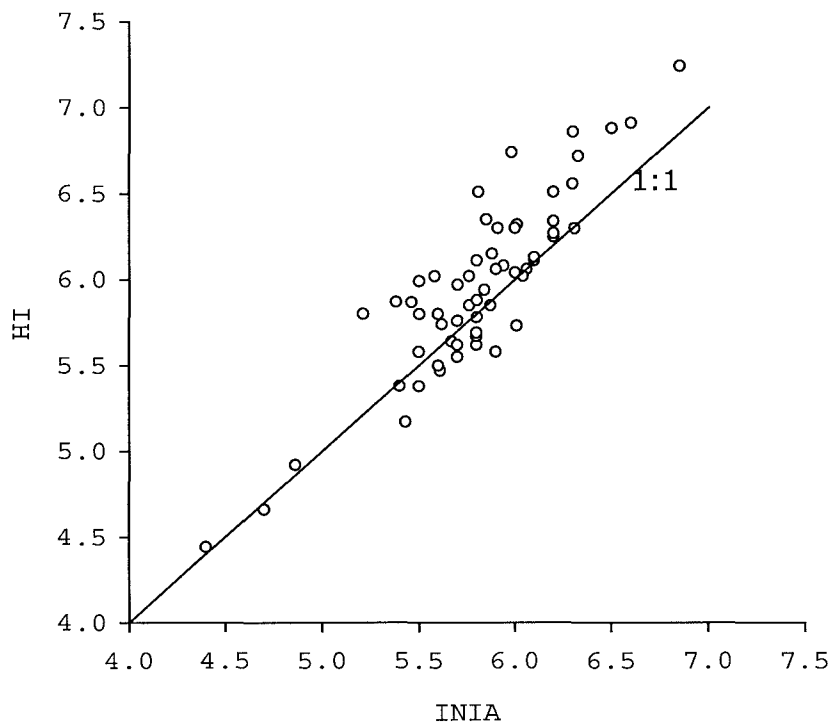


Fig. 17. Comparison of soil pH measured in 1:2.5 soil water ratio by INIA's central laboratory and in 1:1 in Hawaii.

SOIL PARTICLE SIZE DISTRIBUTION

Soil particle-size analysis results show comparable results. The coefficient of correlation was 0.95 for sand fraction, 0.63 for silt and 0.93 for clay.

There is a consistent difference between INIA laboratory analysis and Hawaii's laboratory. INIA's data consistently gives higher values of sand and silt than does the Hawaii laboratory, while the amount of clay was generally lower. This contrast might have been due to differences in the procedures used by INIA central laboratory and in laboratory in Hawaii. Indeed, the measurement of clay and silt fractions depends upon Stokes' Law of Sedimentation (Tyner, 1940; Baver, 1956 and Kilmer, 1949). Therefore, if time, temperature, sampling procedure, removal of organic matter, digestion and dispersion of colloids aggregates with sodium hexametaphosphate are not carefully carried out the results of clay and silt fractions can be misleading.

Grohmann (1976) studied the effect of dispersing methods on soil particle-size in Brazilian Latossolos classified as Oxisols found significant difference in the

percentage of clay when dispersing salts were used or not used. The percentage of clay was 6.5% higher with sodium hexametaphosphate than without it, while the use of the sonic dispersion unit alone was found to have little effect on the percentage of clay. However, this is contrary to what has been reported by many investigators. Genrich and Bremner (1972) and Edwards and Bremner (1971) have indicated that ultrasonic dispersion is more efficient than chemical methods.

TOTAL NITROGEN AND TOTAL CARBON

The percentage of total nitrogen and total carbon by INIA's procedure yielded consistently higher values, contrary to what was expected, because INIA's measurements were conducted with soil moisture approximately at field capacity, which might have yielded lower values rather than higher values as we observed. Although the methods used in both laboratories differed, the differences in the results appeared to be consistent. The coefficient of correlation of total carbon was 0.95 and of total nitrogen was 0.88.

EFFECTIVE CATION EXCHANGE CAPACITY

There was no correlation of effective cation exchange capacity between Hawaii results and INIA central laboratory results. It is not surprising that generally the sum of cations extracted with ammonium acetate buffered at pH 7.0 by INIA's central laboratory was greater than the ECEC obtained with unbuffered solution conducted in Hawaii. It can be predicted from such comparison that these soils have

appreciable variable charge minerals. Therefore, it appears to be more appropriate to estimate exchangeable bases with an unbuffered solution. Fox (1981), investigating some highly weathered soils of Puerto Rico, attributed the discrepancy between CEC measured with NH_4OAc at pH 7 and the sum of exchangeable cations to pH-dependent negative charge, which develops as the pH of the acid soil is altered to near 7. According to Uehara and Gillman (1981) and Gillman et al. (1983) when soils with predominantly variable charge minerals have their pH increased to 7.0, surface charge is increased, which might result in an overestimation of the real charge.

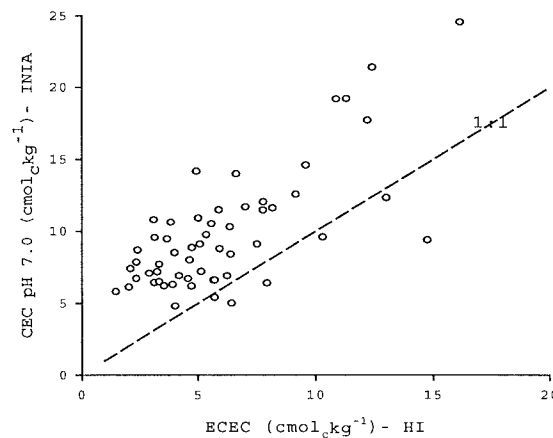


Fig. 18. ECEC measured with ammonium acetate buffered at pH 7.0 by INIA's central laboratory and with mehlich 3 and 1 M KCl solutions by the Hawaii laboratory.

CHAPTER V

CONCLUSION AND RECOMMENDATIONS

Results of this study indicate that low soil fertility is a fundamental problem of agricultural production in Mozambique. Balanced use of a combination of organic and inorganic sources of N and P is crucial for reducing the current decline in soil fertility. In several locations, however, K is not a limiting soil nutrient, and soil fertility trials have revealed no crop response to K application. Nonetheless, 12:24:12 grade has been the most recommended fertilizer resulting in the wasteful application of K.

The majority of the soils have pH within an adequate level; however, in the Barue district located in the central region, the soils have a pH varying from 4.4 to 5.2, suggesting that Al toxicity is likely to occur.

Phosphorus sorption curves show that some soils will retain significant amount of P, leaving a small amount in the soil solution implying that the P fertilizer requirement may be high. This is especially true for 2.5YR

and 10YR (yellowish-red) Rhodic Ferralsols, classified as Oxisols according to the USDA soil classification system. The obvious reason for higher P fertilizer requirement seems to be due to high amounts of gibbsite and goethite.

The X-ray diffraction indicates that kaolinite is the major clay mineral. Goethite and gibbsite are the most common accessory minerals, probably explaining the low ECEC and high P sorption capacity of these soils. Although P sorption curves give insight into the capacity of soil to provide P to the plant-root system, they do not adequately predict how much P is needed. Therefore, calibration and correlation curves are essential in order to make a better estimate of the P requirement.

Decision aids can be useful in soil nutrient management if adapted to site-specific conditions. The prediction of fertilization needs with decision aids indicate fairly good approximations when compared with general N and P fertilizer recommendations developed by INIA (Eshwiler, A. 1986). It is important, however, to recognize the limitations of current fertilizer recommendations developed by INIA, especially for P because they are based on an empirical approach that does not take into account the reactivity of clay and other physical and chemical soil properties. In order to validate NuMaSS and

PDSS predictions, they would have to be tested in Mozambique, through soil fertility experiment.

Geostatistical techniques have the potential of describing the structure and quantifying the spatial dependence of regional variables. This information would help our knowledge of the spatial variability across an entire area and improve our sampling strategy. Analysis of the structure of soil properties indicates different ranges. Consistent correlations were found between total N and total C as well as between soil pH and acidity. It appears that high Al in some areas explains the strength of acidity or low pH, and high correlation between C and N implies that the major N source is from organic matter cycling. Further research, however, should investigate spatial variability with sampling intervals smaller than the average range found in this study.

Soil analysis facilities play an important role in developing fertilizer recommendations. The comparative study between INIA central laboratory results and UH results revealed some similarities and differences. The major discrepancies were observed in effective cation exchange capacity, and consistent differences were observed for N and clay content. The obvious reason was that the analytical procedures were different. As a routine

analysis, INIA determines cation exchange capacity in ammonium acetate buffered to pH 7.0, which usually overestimates the amount of cation exchange capacity, because raising the pH creates additional adsorption sites. In addition, the determination of N with micro-kjeldahl and carbon with Walkley-Black may not be as accurate as the LECO CN 2000 automatic analyzer used by UH.

A number of factors limits the adoption of a fertilization program and its profitability, many of which are out of farmers' control. Developing consistent agricultural policy and improving access to the inputs through retailer chains in the interior farming community as well as training farmers and extension workers in diagnoses and integrated soil fertility management are essential for increasing food production in Mozambique.

This survey gives a general view of soil chemical and physical properties of limited areas in zones of high agricultural potential. It is fundamentally important to conduct a more comprehensive survey of soil fertility of the country, which will provide the opportunity to develop a national fertility map. Priority, however, should be given to zones of cotton production since cotton represents the main cash crop. Geostatistical techniques should be used in mapping cotton production areas.

This study suffers from lack of response curve to the estimated fertilizer and amendment needs. We strongly recommend evaluation of crop response to predicted fertilizer needs for most popular cotton and maize crops.

The current procedure of soil analysis conducted by INIA's central laboratory needs to be revised in order to improve fertilizer recommendations.

APPENDIX I
ESTIMATED N AND P REQUIREMENTS IN SAMPLE SITES OF
MOZAMBIQUE

Predicted N and P requirements for a maize crop

ample #	DISTRICT NAME	N_req kg/ha	P_req (kg/ha)	Sample #	DISTRICT NAME	N_req kg/ha	P_req (kg/ha of P)
1	Montepuez	247.32	11.54	40	Barue	64.39	11.68
2	Montepuez	118.54	12.79	41	Barue	118.54	10.04
3	Montepuez	247.32	14.13	42	Barue	0.00	11.81
4	Montepuez	247.32	12.31	43	Barue	1.46	14.77
5	Montepuez	1.46	15.38	44	Barue	64.39	11.63
6	Montepuez	0.00	14.90	45	Barue	0.00	10.66
8	Montepuez	200.49	13.15	46	Barue	0.00	8.41
9	Montepuez	247.32	12.78	47	Sussudenga	163.90	14.54
10	Montepuez	247.32	13.71	48	Sussudenga	118.54	12.66
11	Montepuez	118.54	13.03	49	Sussudenga	118.54	14.06
12	Montepuez	118.54	13.11	50	Sussudenga	228.29	11.17
13	Montepuez	200.49	11.97	51	Sussudenga	64.39	13.37
14	Montepuez	200.49	13.10	52	Sussudenga	0.00	13.24
15	Netia	228.29	13.54	53	Sussudenga	0.00	13.27
16	Netia	200.49	13.87	54	Manica	118.54	13.78
17	Netia	228.29	13.73	55	Manica	247.32	13.59
18	Netia	118.54	14.56	56	Manica	118.54	13.29
19	Netia	228.29	10.47	57	Gondola	64.39	11.90
20	Netia	163.90	16.91	58	Gondola	118.54	3.77
21	Monapo	163.90	13.37	59	Gondola	1.46	12.88
22	Monapo	247.32	13.36	60	Gondola	163.90	12.11
23	Monapo	118.54	11.47	61	Gondola	200.49	10.19
24	Monapo	228.29	11.39	62	Gondola	163.90	13.45
25	Meconta	0.00	12.92				
26	Meconta	0.00	15.82				
27	Meconta	228.29	13.08				
28	Meconta	0.00	13.14				
29	Gondola	0.00	13.32				
30	Gondola	0.00	13.09				
31	Manica	0.00	12.81				
32	Gondola	0.00	12.94				
33	Gondola	0.00	13.19				
34	Inchope	118.54	6.95				
35	Inchope	64.39	11.36				
36	Gondola/Matsir	64.39	13.53				
37	Gondola	200.49	13.62				
38	Barue	200.49	16.71				
39	Barue	1.46	13.30				

APPENDIX II

X-RAY DIFRACTION DATA OF SELECTED SOILS OF MOZAMBIQUE

Sample #	2-Theta	d(A)	Sample #	2-Theta	d(A)	Sample #	2-Theta	d(A)	Sample #	2-Theta	d(A)
4	8.416	10.4973	12	8.845	9.9895	15	20	4.4359	21	12.772	6.9255
4	12.349	7.1618	12	11.965	7.3903	15	20.45	4.3392	21	12.94	6.8359
4	17.839	4.9679	12	12.235	7.2281	15		4.2407	21	13.555	6.5269
4	20.243	4.3831	12	17.787	4.9824	15	24.1039	4.1403	21	20.761	4.2749
4	20.504	4.328	12	19.884	4.4616	15	26.8424	3.5659	21	21.202	4.1871
4	20.924	4.242	12	20.894	4.248	15	29.5808	3.5163	21	23.011	3.8618
4	21.401	4.1486	12	21.066	4.2138	15	32.3193	3.4615	21	23.119	3.844
4	23.126	3.8429	12	21.329	4.1624	15	35.0578	3.4077	21	25.582	3.4792
4	24.95	3.5658	12	23.548	3.775	15	26.724	3.3331	21	27.255	3.2693
4	25.555	3.4828	12	24.831	3.5826	16	11.206	7.8894	21	30.132	2.9634
4	26.689	3.3374	12	25.124	3.5416	16	12.406	7.1287	21	33.861	2.6451
4	27.479	3.2431	12	25.52	3.4875	16	18.351	4.8305	21	33.973	2.6366
10	8.486	10.4111	12	26.718	3.3338	16	19.384	4.5755	21	36.329	2.4709
10	8.747	10.101	12	27.406	3.2516	16	20.056	4.4236	21	36.514	2.4588
10	12.229	7.2316	12	27.896	3.1956	16	20.194	4.3937	21	37.827	2.3764
10	19.88	4.4623	12	28.57	3.1217	16	20.749	4.2774	21	38.283	2.3491
10	20.421	4.3454	13	12.381	7.1433	16	21.472	4.135	21	38.449	2.3393
10	20.713	4.2847	13	17.954	4.9364	16	22.583	3.934	22	6.41	13.7773
10	21.259	4.176	13	18.406	4.8164	16	25.042	3.553	22	8.87	9.9616
10	22.558	3.9383	13	19.974	4.4416	16	30.02	2.9742	22	12.38	7.1435
10	24.857	3.5791	13	20.332	4.3641	16	33.318	2.687	22	17.851	4.9647
10	26.303	3.3855	13	20.607	4.3066	16	33.76	2.6527	22	20.105	4.413
10	26.519	3.3584	13	21.527	4.1246	16	35.819	2.5049	22	21.379	4.1527
10	27.381	3.2546	13	25.038	3.5536	16	35.975	2.4944	22	24.981	3.5615
11	12.41	7.1267	13	25.682	3.4658	16	37.934	2.3699	22	26.75	3.3299
11	19.919	4.4538	13	32.902	2.72	19	8.926	9.8986	22	33.347	2.6847
11	20.902	4.2464	13	33.202	2.696	19	12.259	7.214	22	35.896	2.4997
11	21.074	4.2122	13	33.381	2.682	19	18.252	4.8565	22	37.851	2.3749
11	23.329	3.8098	13	33.558	2.6683	19	19.908	4.4562	26	2.25	39.2285
11	23.615	3.7644	13	35.841	2.5034	19	20.239	4.384	26	12.204	7.2462
11	25.008	3.5577	13	37.82	2.3768	19	20.57	4.3143	26	18.378	4.8236
11	26.546	3.355	15	8.774	10.0702	19	21.262	4.1753	26	19.907	4.4565
11	26.93	3.308	15	8.916	9.9099	19	21.436	4.1418	26	21.466	4.1361
11	27.531	3.2372	15	12.381	7.143	19	24.803	3.5867	26	24.895	3.5736
11	29.577	3.0177	15	16.595	5.3375	21	11.575	7.6388	26	28.484	3.1309

Sample #	2-Theta	d(A)	Sample #	2-Theta	d(A)	Sample #	2-Theta	d(A)	Sample #	2-Theta	d(A)
26	29.121	3.0639	29	37.936	2.3698	33	36.652	2.4498	38	29.951	2.9809
26	32.935	2.7173	31	9.047	9.7672	33	37.756	2.3807	38	30.216	2.9553
26	33.176	2.6981	31	12.561	7.0414	33	38.137	2.3578	38	31.294	2.856
26	35.526	2.5249	31	18.535	4.783	33	38.483	2.3373	38	31.428	2.8441
26	35.886	2.5003	31	20.132	4.4072	33	39.233	2.2944	38	33.004	2.7118
26	37.786	2.3788	31	20.43	4.3434	36	8.985	9.8341	38	33.256	2.6918
26	38.049	2.363	31	20.798	4.2675	36	12.471	7.0917	38	33.51	2.672
28	8.32	10.6181	31	25.13	3.5408	36	18.495	4.7934	38	33.734	2.6547
28	8.813	10.0257	31	26.872	3.315	36	20.061	4.4224	38	35.091	2.5551
28	9.032	9.7833	31	32.33	2.7668	36	20.183	4.396	38	35.891	2.5
28	9.191	9.6137	31	34.372	2.6069	36	21.461	4.1372	38	36.041	2.4899
28	12.379	7.1446	31	34.505	2.5972	36	21.622	4.1067	38	36.534	2.4575
28	17.751	4.9925	31	35.14	2.5517	36	25.069	3.5492	38	36.613	2.4523
28	17.953	4.9367	31	35.343	2.5375	36	26.783	3.3258	38	37.73	2.3823
28	19.943	4.4484	31	35.658	2.5158	38	8.36	10.5676	38	38.025	2.3645
28	21.573	4.1159	31	36.187	2.4802	38	8.871	9.9604	38	38.521	2.3352
28	21.733	4.0858	31	37.895	2.3723	38	10.483	8.4319	40	9.024	9.7914
28	24.978	3.562	31	38.693	2.3252	38	11.131	7.9422	40	12.531	7.0579
28	26.52	3.3582	31	39.48	2.2806	38	12.377	7.1453	40	18.047	4.9113
28	26.69	3.3372	33	9.052	9.7612	38	16.129	5.4906	40	20.12	4.4098
28	34.371	2.607	33	9.052	9.7612	38	16.513	5.364	40	21.53	4.1239
28	35.484	2.5278	33	9.434	9.3669	38	17.923	4.9449	40	25.101	3.5448
28	35.733	2.5107	33	12.32	7.1787	38	18.343	4.8327	40	26.958	3.3047
28	35.954	2.4958	33	18.064	4.9068	38	19.903	4.4573	40	33.68	2.6589
28	37.795	2.3783	33	18.316	4.8398	38	20.328	4.365	40	36.078	2.4875
29	9.019	9.7971	33	18.65	4.7538	38	20.581	4.312	40	37.968	2.3679
29	12.5	7.0755	33	19.943	4.4485	38	21.356	4.1572	48	8.684	10.1744
29	17.955	4.9363	33	20.294	4.3722	38	24.201	3.6745	48	8.803	10.0366
29	18.518	4.7874	33	20.505	4.3276	38	24.937	3.5677	48	12.263	7.2118
29	20.148	4.4036	33	21.473	4.1347	38	25.648	3.4704	48	17.878	4.9572
29	25.07	3.5491	33	24.889	3.5744	38	26.219	3.3961	48	18.288	4.8472
29	26.752	3.3297	33	32.893	2.7207	38	26.838	3.3192	48	19.939	4.4493
29	34.505	2.5972	33	33.282	2.6898	38	27.932	3.1916	48	20.272	4.3769
29	35.185	2.5485	33	34.963	2.5642	38	28.676	3.1105	48	20.509	4.327
29	36.052	2.4892	33	35.781	2.5074	38	29.624	3.013	48	21.353	4.1577

Sample #	2-Theta	d(A)	Sample #	2-Theta	d(A)	Sample #	2-Theta	d(A)	Sample #	2-Theta	d(A)
48	24.919	3.5702	50	17.778	4.9849	55	29.872	2.9886	56	20.133	4.4068
48	26.636	3.3438	50	18.269	4.852	55	31.231	2.8616	56	20.262	4.3791
48	33.531	2.6704	50	19.851	4.4688	55	32.036	2.7915	56	20.422	4.3451
48	33.971	2.6368	50	21.293	4.1694	55	33.639	2.662	56	21.144	4.1984
48	35.029	2.5595	50	21.406	4.1476	55	34.997	2.5618	56	21.592	4.1122
48	35.571	2.5217	50	21.653	4.1007	55	35.96	2.4954	56	24.432	3.6403
48	35.787	2.507	50	24.89	3.5744	55	37.582	2.3913	56	25.156	3.5371
48	35.958	2.4955	50	26.604	3.3479	55	37.737	2.3819	56	26.927	3.3084
48	37.122	2.4199	50	32.991	2.7129	55	8.837	9.9984	56	28.845	3.0927
48	37.816	2.3771	50	33.182	2.6977	55	12.261	7.2128	56	33.472	2.6749
48	38.397	2.3424	50	33.377	2.6823	55	17.751	4.9925	56	33.65	2.6612
48	38.57	2.3323	50	34.997	2.5618	55	18.191	4.8726	56	35.302	2.5404
48	8.684	10.1744	50	35.838	2.5036	55	19.879	4.4625	56	36.052	2.4892
48	8.803	10.0366	50	36.009	2.4921	55	20.182	4.3964	56	36.386	2.4671
48	12.263	7.2118	50	36.902	2.4338	55	20.896	4.2477	56	37.973	2.3676
48	17.878	4.9572	50	37.157	2.4177	55	21.375	4.1535	60	8.6	10.2735
48	18.288	4.8472	50	37.762	2.3803	55	21.494	4.1308	60	8.821	10.0166
48	19.939	4.4493	50	38.329	2.3464	55	24.948	3.5661	60	12.322	7.1775
48	20.272	4.3769	50	38.46	2.3387	55	25.454	3.4964	60	17.779	4.9846
48	20.509	4.327	50	39.442	2.2827	55	26.661	3.3408	60	19.999	4.4361
48	21.353	4.1577	55	8.837	9.9984	55	27.459	3.2455	60	20.685	4.2905
48	24.919	3.5702	55	12.261	7.2128	55	27.904	3.1947	60	20.968	4.2332
48	26.636	3.3438	55	17.751	4.9925	55	28.616	3.1169	60	24.949	3.566
48	33.531	2.6704	55	18.191	4.8726	55	29.872	2.9886	60	25.306	3.5166
48	33.971	2.6368	55	19.879	4.4625	55	31.231	2.8616	60	26.698	3.3362
48	35.029	2.5595	55	20.182	4.3964	55	32.036	2.7915	60	33.547	2.6691
48	35.571	2.5217	55	20.896	4.2477	55	33.639	2.662	60	35.029	2.5596
48	35.787	2.507	55	21.375	4.1535	55	34.997	2.5618	60	35.754	2.5093
48	35.958	2.4955	55	21.494	4.1308	55	35.96	2.4954	60	35.932	2.4973
48	37.122	2.4199	55	24.948	3.5661	55	37.582	2.3913	60	37.511	2.3956
48	37.816	2.3771	55	25.454	3.4964	55	37.737	2.3819	60	37.849	2.3751
48	38.397	2.3424	55	26.661	3.3408	56	9.072	9.7395	60	38.571	2.3322
48	38.57	2.3323	55	27.459	3.2455	56	12.557	7.0437	60	38.81	2.3184
50	8.836	10	55	27.904	3.1947	56	18.022	4.9181			
50	12.26	7.2134	55	28.616	3.1169	56	18.565	4.7755			

APPENDIX III
PHOSPHORUS SORPTION DATA

Sample no.	P remaining in solution (ug/mL)	P sorbed (ug/g)	Sample no.	P remaining in solution (ug/mL)	P sorbed (ug/g)	Sample no.	P remaining in solution (ug/mL)	P sorbed (ug/g)	Sample no.	P remaining in solution (ug/mL)	P sorbed (ug/g)
1	0.034	-0.337	12	0.000	0.000	20	0.000	0.000	28	0.018	-0.183
1	0.217	19.700	12	0.002	24.977	20	0.009	24.909	28	0.016	24.843
1	1.147	38.526	12	0.039	49.615	20	0.025	49.751	28	0.029	49.712
1	4.311	56.890	12	0.299	97.007	20	0.231	97.687	28	0.288	97.122
1	8.794	112.064	12	1.905	180.952	20	1.531	184.694	28	3.048	169.519
2	0.001	-0.010	13	0.011	-0.112	21	0.000	-0.020	29	0.007	-0.068
2	0.025	24.755	13	0.107	23.931	21	0.010	24.860	29	0.018	24.819
2	0.129	48.710	13	0.602	43.982	21	0.040	49.640	29	0.156	48.435
2	0.537	94.630	13	2.781	72.188	21	0.090	78.340	29	0.778	92.222
2	1.406	185.940	13	6.015	139.848	21	2.650	173.470	29	2.957	170.431
3	0.010	-0.105	14	0.011	-0.112	22	0.020	-0.170	30	0.003	-0.028
3	0.199	23.012	14	0.104	23.960	22	0.040	16.000	30	0.042	24.578
3	1.018	39.822	14	0.380	46.204	22	0.630	43.730	30	0.101	48.988
3	3.925	60.754	14	1.850	81.496	22	1.990	80.060	30	0.290	97.103
3	8.375	116.248	14	6.038	139.623	22	6.390	136.080	30	3.296	167.042
4	0.010	-0.105	15	0.000	0.000	23	0.000	0.000	31	0.005	-0.045
4	0.353	21.468	15	0.000	25.000	23	0.177	23.228	31	0.000	25.000
4	1.361	36.395	15	0.025	49.751	23	0.295	47.047	31	0.007	49.932
4	3.844	61.565	15	0.272	97.279	23	1.572	84.280	31	0.125	98.753
4	7.436	125.641	15	2.925	170.748	23	5.599	144.010	31	0.778	192.222
5	0.020	-0.200	16	0.006	-0.056	24	0.006	-0.056	32	0.000	-0.020
5	0.040	24.610	16	0.014	24.859	24	0.318	21.822	32	0.000	25.000
5	0.090	49.210	16	0.037	49.634	24	1.263	37.373	32	0.010	66.000
5	0.680	93.220	16	0.143	98.566	24	4.213	57.874	32	0.010	99.910
5	3.550	164.510	16	1.257	187.430	24	9.336	106.637	32	0.060	199.430
6	0.010	-0.110	17	0.040	-0.420	25	0.017	-0.169	33	0.000	-0.030
6	0.030	24.910	17	0.080	24.210	25	0.017	24.831	33	0.010	24.940
6	0.070	49.340	17	0.180	49.040	25	0.042	49.578	33	0.010	49.910
6	0.550	94.490	17	0.750	92.550	25	0.290	97.103	33	0.020	99.910
6	3.190	168.070	17	4.210	157.930	25	1.457	185.433	33	0.090	199.060
8	0.005	-0.052	18	0.006	-0.056	26	0.000	0.000			
8	0.052	24.477	18	0.326	21.738	26	0.017	24.831			
8	0.557	44.427	18	1.448	35.517	26	0.025	49.747			
8	2.624	73.757	18	4.440	55.596	26	0.112	98.875			
8	7.467	125.327	18	10.011	99.888	26	0.571	194.291			
9	0.002	-0.023	19	0.000	0.000	27	0.014	-0.136			
9	0.077	24.229	19	0.502	19.976	27	0.172	23.277			
9	0.390	46.100	19	1.735	32.653	27	0.984	40.159			
9	1.776	82.245	19	4.406	55.939	27	3.229	67.710			
9	5.367	146.327	19	9.223	107.771	27	7.401	125.986			

Sample no.	P remaining in solution (ug/mL)	P sorbed (ug/g)	Sample no.	P remaining in solution (ug/mL)	P sorbed (ug/g)	Sample no.	P remaining in solution (ug/mL)	P sorbed (ug/g)	Sample no.	P remaining in solution (ug/mL)	P sorbed (ug/g)
35	0.000	0.000	43	0.005	-0.045	51	0.01	-0.090	59	0.098	49.025
35	0.000	25.000	43	0.007	24.932	51	0.05	24.950	59	1.456	85.442
35	0.120	48.820	43	0.073	49.274	51	0.18	48.250	59	3.417	165.828
35	0.230	99.020	43	0.853	91.474	51	2.89	171.070	60	0.000	0.000
35	0.600	194.010	43	3.401	165.986	52	0.65	111.300	60	0.082	24.184
36	0.010	27.000	44	0.008	-0.078	52	0.003	24.974	60	0.405	45.951
36	0.000	24.970	44	0.063	24.372	52	0.005	49.948	60	2.160	78.403
36	0.030	49.740	44	0.246	47.541	52	0.235	197.645	60	6.558	134.421
36	0.170	98.350	44	1.172	88.278	53	0.009	-0.091	61	0.006	-0.056
36	0.890	191.080	44	4.652	153.480	53	0.011	24.887	61	0.121	23.791
37	0.000	-0.140	45	0.013	-0.131	53	0.016	49.841	61	0.290	47.103
37	0.010	25.000	45	0.034	24.660	53	0.066	99.342	61	1.530	84.702
37	0.080	49.180	45	0.055	49.451	53	0.338	196.621	61	5.644	143.560
37	0.360	96.400	45	0.136	98.639	54	0.007	-0.068	62	0.014	-0.141
37	2.190	178.120	45	0.612	193.878	54	0	25.000	62	0.025	24.747
38	0.020	-0.200	46	0.010	-0.050	54	0.009	49.909	62	0.045	49.550
38	0.040	24.490	46	0.010	24.890	54	0.014	99.864	62	0.079	99.213
38	0.050	49.800	46	0.020	49.950	54	0.045	199.546	62	0.425	195.754
38	0.080	99.210	46	0.190	98.120	55	0.034	-0.340			
38	0.340	196.650	46	1.070	189.300	55	0.110	23.901			
39	0.000	0.000	47	0.008	-0.084	55	1.033	39.665			
39	0.000	25.000	47	0.014	24.859	55	3.770	62.297			
39	0.000	50.000	47	0.022	49.775	55	9.061	109.393			
39	0.042	99.581	47	0.112	98.875	56	0.000	0.000			
39	0.254	197.462	47	0.740	192.604	56	0.008	24.916			
40	0.014	-0.141	48	0.03	-0.310	56	0.034	49.663			
40	0.017	24.831	48	0.04	24.720	56	0.250	97.497			
40	0.070	49.297	48	0.05	49.470	56	1.057	189.426			
40	0.301	96.991	48	0.19	98.140	57	0.008	-0.084			
40	1.960	180.399	48	1.21	187.910	57	0.067	24.325			
41	0.021	-0.209	49	0.005	-0.052	57	0.349	46.513			
41	0.240	22.650	49	0.003	24.974	57	1.437	85.630			
41	0.840	63.100	49	0.005	49.948	57	4.722	152.784			
41	1.350	86.500	49	0.073	99.267	58	0.022	-0.225			
41	6.500	134.980	49	0.612	193.878	58	0.135	23.650			
42	0.008	-0.084	50	0.006	-0.056	58	0.596	44.038			
42	0.045	24.550	50	0.157	23.425	58	2.011	79.893			
42	0.143	48.566	50	0.996	40.045	58	6.493	135.067			
42	0.779	92.210	50	3.38	66.198	59	0.000	0.000			
42	3.130	168.701	50	6.817	131.834	59	0.005	24.955			

APPENDIX IV

DETERMINING THE LIMING EQUIVALENT OF A LIMING MATERIAL

DETERMINING THE LIMING EQUIVALENT OF A LIMING MATERIAL

INTRODUCTION

Soil acidity is one of the most limiting constraints to agricultural productions in many areas of the tropics. The most important factor contributing to high acidity is high rainfall, which causes the leaching of bases and the formation of more stable materials rich in aluminium and iron. The hydrolysis of aluminium and iron causes an increase of H^+ in the soil, leading to either Ca^{2+} and Mg^{2+} deficiencies or to Al^{3+} and Mn^{2+} toxicity. Other factors that cause soil acidity are parent material and removal of bases by the crop.

The detrimental effects of soil acidity can be reduced either with the use of liming material or with the adoption of acid tolerant crops. When liming material is added to the soil, three steps of the neutralizing process take place. The first step is the dissolution of the liming material; the second is the exchange of Ca with Al^{3+} and H^+ on the surface of the colloids; and the third is the reaction of Al^{3+} or H^+ with OH^- produced from the liming material.

The effectiveness of liming materials in neutralizing soil acidity depends to a considerable extent on its particle-size. Generally, fine-sized material has higher reactivity; therefore more rapid neutralizing capacity than coarse material, as illustrated in the Figure below for limestone. This property is denoted as effective calcium carbonate equivalent (ECCE). Knowing the ECCE is crucial for selecting the appropriate liming material for better crop production.

ABSTRACT

This experiment analyzes how much acidity the liming material can neutralize using the titration method. The procedure used is outlined in an analytical liming method developed by the Soil Analysis Center in Lincoln, Nebraska. The sample was oven dried for twenty-four hours after which 0.5M HCl was added to 1 gram of the sample. The excess of HCl, was measured after 24 hours with titration with 0.304M NaOH in repeated measurements. The NaOH was standardized against 0.5M HCl.

For verification purposes of the analytical procedure, pure CaCO_3 was also tested following the same method outlined above. The results show that liming material had more than 100% of a liming equivalent. The standard error for liming material was 0.27 and for pure CaCO_3 was 0.17.

METHODS

Measurement of moisture contents

To measure the moisture content of both the liming material sample and the pure CaCO_3 , they were oven dried at 105°C for 24 hours. The percentage of water was computed as follows:

$$\% \text{H}_2\text{O} = (\text{total wet} - \text{total dry wt}) / (\text{total dry wt} - \text{can wt}) * 100\%.$$

Eq. [1]

Where:

total wet wt = can weight + wet lime

total dry weight = can wet + dry lime

Measuring the liming equivalent

One gram of oven dried liming material reacted with 50 mL of 0.5M HCl in approximately 50 mL of dionized water. The sample was digested below boiling point in a heater for twenty minutes and left for 24 hours. The experiment was conducted in six replicates. The excess acid was reacted with 0.307 M standardized NaOH. The results, shown in the Figure below, indicate the amount of NaOH consumed in the titration. The same procedure was used for pure CaCO_3 .

1. Standardizing NaOH

The NaOH was standardized against 0.5 M HCl with bromthymol blue as an indicator. The standardization was conducted in six replications. The standardized concentration of NaOH was calculated as follows:

$$\text{Molarity of NaOH} = \frac{\text{ccHCl}}{\text{ccNaOH}} \quad \text{Eq. [2]}$$

Where

cc HCl - volume of HCl

cc NaOH - Volume of NaOH consumed in the titration.

Calculating the liming equivalent

The liming equivalent was calculated as follows:

$$\% \text{CaCO}_3 = 250 * M \text{ HCl} - 5 * (M \text{ NaOH} * \text{ml NaOH}) \quad \text{Eq. [3]}$$

RESULTS AND DISCUSSION

The moisture content of the liming material was 0.99% and of pure CaCO_3 was 0.07%. The mean of the total NaOH consumed in the reaction with CaCO_3 was 5.13 ml, roughly four times as much as that consumed in the liming material (Fig. 1). However, the standard deviation of the liming material was found to be slightly higher than that of the pure CaCO_3 . The higher value of standard error might be due to the physical makeup of the liming material. Finer liming material has a higher surface area, hence a higher reactivity than big particles. This property is important in determining the effectiveness of the liming material, known as effective calcium carbonate equivalent.

The liming equivalent of the liming material was 117.14% and the margin of error of titration of pure CaCO_3 was approximately 5%.

The CaCO_3 has been assumed as standard and corresponds to 100% in calculating the lime equivalent. The liming material tested shows a higher neutralizing power than pure CaCO_3 , a difference that suggests that it might likely be dolomite limestone ($\text{CaMg}(\text{CO}_3)$) or burnt lime₂, which has the

calcium carbonate equivalent of 109. Table 1 indicates the common liming materials and their neutralizing powers.

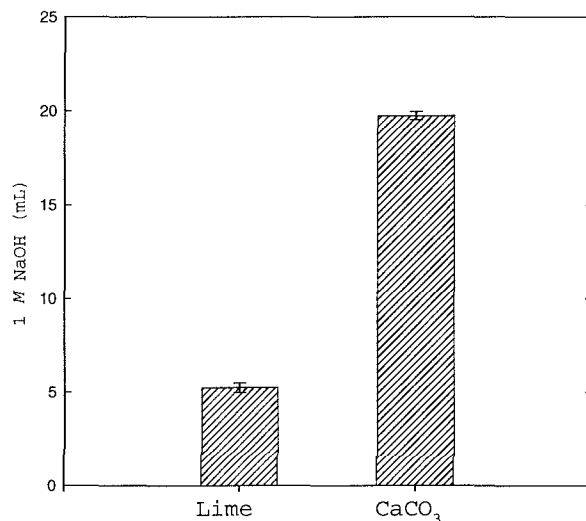


Fig. 1. Amount of NaOH used to neutralize the excess acid after reacting with 1 g of CaCO₃.

TABLE 1. Common liming sources, their composition and calcium carbonate equivalence

Liming Typical	Molecular Wt. (g/mole)	Neutralizing Value (%)
Limestone (calcitic) CaCO ₃	100	100
Dolomitic lime CaMg(CO ₃) ₂	184	109
CaSiO ₃	116	86
Burned lime CaO	56	179
Hydrated (slaked) lime Ca(OH) ₂	72	136

Source: Havlin (1999).

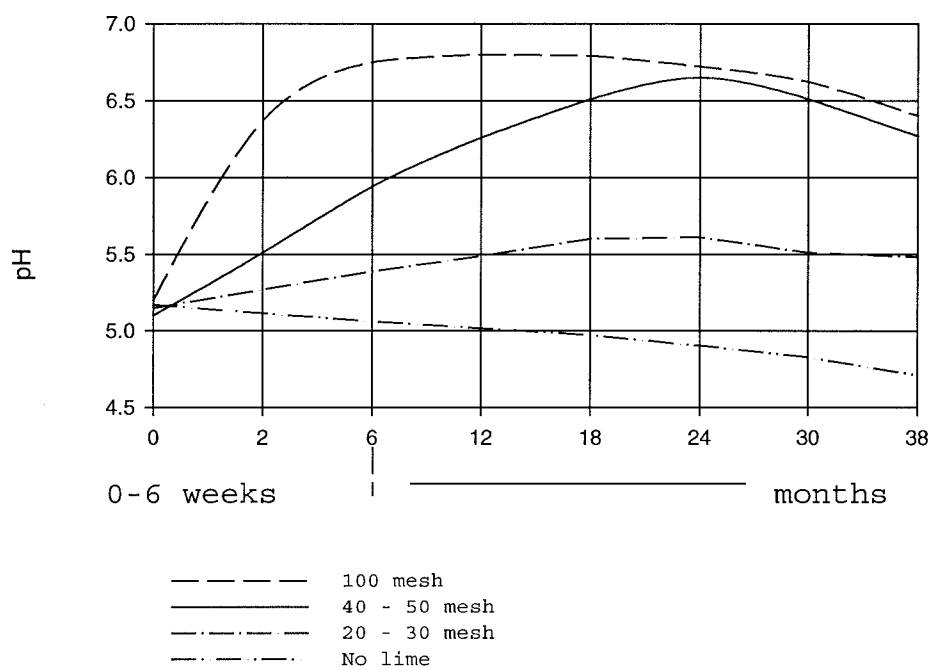


Fig. 1. Effect of particle size on rate of limestone reactivity.

CONCLUSION

Clearly, the liming material has a higher neutralizing power than does pure CaCO_3 .

The variation in the size of the aggregates might have contributed to their higher standard error than exists in pure CaCO_3 .

To determine the precise nature of the liming material further tests are recommended. Such tests can be determining the elemental composition of the liming material.

RESULTS OF LAB ANALYSIS AND DEMONSTRATION OF THE
COMPUTATIONS

Data:

Standardization of NaOH

Volume of NaOH

30.8 ml

30.2 ml

30.8 ml

30.5 ml

30.8 ml

30.8 ml

$$\text{Normality of NaOH} = \frac{\text{cc HCl}}{\text{cc NaOH}}$$

$$\text{Normality of NaOH} = 0.5 \times \frac{30.65}{50}$$

$$\text{Normality of NaOH} = 0.3065$$

Mean of HCl = 30.65 ml

Liming material

a) Moisture content

Total wet wt = 97.83

Total dry wt = 97.07

Can wt = 20.34

$$\begin{aligned} \% \text{ H}_2\text{O} &= \frac{\text{total wet wt} - \text{total dry wt}}{\text{total dry wt} - \text{can wt}} \times 100\% \\ &= \frac{97.83 - 97.07}{97.07 - 20.34} \times 100 \\ &= 0.99\% \end{aligned}$$

b) Lime equivalent

Volume of NaOH

$$V_1 = 5.2 \text{ ml}$$

$$V_2 = 5.3 \text{ ml}$$

$$V_3 = 4.9 \text{ ml}$$

$$\text{Mean} = \underline{5.13 \text{ ml}}$$

$$\begin{aligned} \% \text{CaCO}_3 &= 250 \cdot \text{NHCl} - 5 \cdot (N \text{ NaOH} \cdot \text{mL NaOH}) \\ &= 250 \cdot 0.5 - 5 \cdot (0.3065 \cdot 5.13) \\ &= 117.14 \% \end{aligned}$$

Calcium Carbonate material

a) Moisture content

$$\begin{aligned} \text{Total wet wt} &= 37.20 \\ \text{Total dry wt} &= 37.18 \\ \text{Can wt} &= 8.903 \end{aligned}$$

$$\begin{aligned} \% \text{H}_2\text{O} &= \frac{\text{total wet wt} - \text{total dry wt}}{\text{total dry wt} - \text{can wt}} \times 100\% \\ &= \frac{37.20 - 37.18}{37.18 - 8.903} \times 100 \\ &= 0.07\% \end{aligned}$$

Volume of NaOH

$$V_1 = 19.5 \text{ ml}$$

$$V_2 = 19.7 \text{ ml}$$

$$V_3 = 19.7 \text{ ml}$$

$$V_3 = 20.0 \text{ ml}$$

$$V_3 = 19.7 \text{ ml}$$

$$\text{Mean} = \underline{19.73 \text{ ml}}$$

$$\begin{aligned} 250 \cdot \text{NHCl} - 5 \cdot (N \text{ NaOH} \cdot \text{ml NaOH}) \\ &= 250 \cdot 0.5 - 5 \cdot (0.3065 \cdot 19.73) \\ &= 94.8\% \end{aligned}$$

APPENDIX IV
COMPOSITION OF COMMON FERTILIZERS

TABLE 2. Composition of some common fertilizers

	%N-P ₂ O ₅ -K ₂ O
Nitrogen Fertilizers	
Ammonium Nitrate	33.5-0-0
Ammonium Sulfate	20-0-0
Calcium Nitrate	5-0-0
Potassium Nitrate	13-0-44
Sodium Nitrate	16-0-0
Nitrate of Soda Potash	15-0-16
Monoammonium Phosphate	11-48-0
Diammonium Phosphate	18-46-0
Urea	45-0-0
Calcium Cyanamide	21-0-0
Ureaform/Nitroform	38-0-0
Nutralene	40-0-0
Isobutylidene diurea (IBDU)	31-0-0
Sulfur-coated Urea	38-0-0
Polyon	42-0-0
Sewage Sludge	6-2-0
Cow Manure	2-0-0
Poultry Manure	4-0-0
Cottonseed Meal	7-0-0
Alfalfa Meal	6-0-0
Blood Meal	3-22-0
Processed Tankages	5-10 (varies)
Garbage Tankages	2-3 (varies)
Some Commercial Sources of Potassium and Phosphorus Fertilizers	
Potassium Chloride (Muriate of Potash)	0-0-6
Potassium Sulfate	0-0-50
Potassium Nitrate	13-0-44
Sulfate of Potash Magnesia	0-0-22, 11% Mg, 8% S
Concentrated Superphosphate	0-46-0

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