A SURVEY OF SOIL FERTILITY STATUS OF FOUR AGROECOLOGICAL ZONES OF MOZAMBIQUE

Ricardo M. Maria and Russell Yost

Mozambique includes 10 agroecological zones with distinct climate and cropping systems (INIA, 1980). Agricultural production is more intensively practiced in the central and northern parts of the country where agroecological conditions are favorable. As a result of 16 years of civil war and low funding for agricultural research few assessments of soil nutrient status have been possible. To assess soil nutrient status, four agriculturally promising agroecological zones were selected for a survey. Sixty-two sites were sampled, and composite samples of surface and subsurface soils were taken and analyzed for properties considered critical for the production of food crops. The sample points were recorded with a differential global position system and mapped. The results indicate that most of the soils are low in effective cation exchange capacity, moderate in organic matter, moderate to strongly acidic, moderately weathered, and moderate to high in P sorption capacity. In general, these soils can be classified as having low to moderate fertility. Findings of this study indicate limitations of the existing map of soil resources of Mozambique. The results of this study suggest that additional sampling and soil survey will be required to improve the quality of soil surveys for site-specific applications. A site-specific soil survey is recommended that would provide additional information on soil resources and would greatly improve the current soil map that has an inadequate soil database. Furthermore, calibration and correlation studies are recommended for better decisions on soil nutrient management for ensuring food security. (Soil Science 2006;171:902-914)

Key words: Nutrient management, maize, cotton, sorghum, P, soil mapping.

MOZAMBIQUE, recently announced as one of the Millenium Challenge countries of Africa, is only recently recovering from 16 years of a devastating civil war and resulting famine. The agricultural sector contributes up to 25% of the gross domestic product and 65% of the total value of exports. Nevertheless, little information is currently available for farmers and extension workers to use in making informed decisions on soil and nutrient management to improve selection and crop production. Field surveys have consistently indicated that low soil fertility is a limiting factor. Folmer et al., (1998) attempted

to predict zones of potential nutrient problems with a mathematical model based on land units and land use systems. Although his study indicates which areas are likely to have soil fertility problems, it does not provide information for estimating plant nutrient requirements nor does it provide site-specific recommendations.

A survey of soil fertility status, which includes soil sampling and analysis, would provide valuable information for diagnosis and prediction of fertilization needs. The objective of this study was to begin such an inventory and assessment of soil nutrient status, which could lead to effective site-specific soil nutrient management and better use of soil resources and increased food security. The result of this survey could also be the beginning of calibration and correlation studies for specific agroecological zones of Mozambique.

Instituto de Investigação Agrária de Moçambique and University of Hawaii at Manoa. Dr. Yost is corresponding author. E-mail: rsyost@hawaii.edu

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MATERIAL AND METHODS

Main Features of Study Locations

Ten agroecological zones (AEZ) of Mozambique have been identified, based on climate, soil type, elevation, and farming system. Four of these zones represent vast areas, covering one or more Food and Agriculture Organization (FAO) soil units. A summary description of each of the AEZ (R) is given as follows:

High Elevation, Inland Manica Province (R10)

The R10 region is high elevation, situated 1000 m above sea level. The mean annual rainfall exceeds 1200 mm. The mean annual temperature is between 15 and 22 degrees. The predominant soils are probably Ultisols of high clay content. The main crops are maize, sorghum, millet, and finger millet.

Medium Elevation Manica Province (R4)

The R4 region includes land between 200 and 1000 m above sea level. The annual rainfall ranges from 1000 to 1200 mm. The main food crops are maize, sorghum, and millet. There is a high potential for cotton production in this region. The predominant soil type is probably Oxisols with low fertility. The risk of soil erosion in some areas is very high because of topography of the terrain.

Coastal Littoral of Nampula (R8)

In this region, the average temperature is higher than 25 °C. The range of annual rainfall is between 800 and 1200 mm, and the evapotranspiration is more than 1400 mm. The predominant soil type in this agroecological region is Alfisols. Cotton is the main cash crop cultivated by small-scale sector and joint venture companies. Other crops cultivated in great extent are maize, sorghum, millet, and cassava.

Inland of Nampula and Cabo Delgado (R7)

The AEZ 7 is a vast region in the northern Mozambique. The elevation ranges from 200 to 1000 m above sea level. The annual rainfall ranges from 1000 to 1400 mm. There is variability in soil type. The most predominant soils are probably Ultisols and Oxisols. There is a problem of soil acidity in this region, especially in the plateau region.

Most of the crops cultivated are maize, cassava, groundnut, and beans. Cotton is the most important cash crop and is cultivated both by small-scale farmers and joint venture cotton production companies.

Selection of Soil Sample Locations

The soil sampling plan covered four agroecological regions, two in northern Mozambique (R7 and R8), and two in the central provinces of the country (R4 and R10) (Fig. 1). Criteria for selecting those regions were (i) high potential for food production, (ii) existence of potential users, (iii) presence of excellent agricultural support services, and (iv) high accessibility by roads. In the absence of a detailed soil classification map, the selection of sites for soil sampling in each location was conducted based on district extension workers' knowledge of existing agricultural potential and the approximate distribution of soils in the area. Soil samples were taken from unfertilized agricultural land following an approximately random pattern. At each of the 64 sites, three subsamples were composited from the depths of 0 to 15 cm and 15 to 30 cm using a soil auger. The sample locations were recorded using a differential global position system unit Trimble GeoExplorer 3, Sunnyvale, CA.

Laboratory Analysis

Soil Analysis

Soil samples were analyzed for color, particle size, pH, and effective cation exchange capacity (ECEC). The soil air-dry color was determined with Munsell soil color chart outside of the laboratory during the noon hours, and the particle size was determined by the pipette method after destruction of the organic matter (OM) with hydrogen peroxide and dispersion with sodium hexametaphosphate (Gee and Bauder, 1986). The pH was measured with a glass electrode in a 1:1 soil-water suspension and in a 1:1 soil-1 M KCl suspension. The electrical conductivity was determined in a 1:2.5 soil-water suspension. The exchangeable bases (Na, Ca, and Mg) and Al were extracted with 1 M KCl in a 1:50 ratio in duplicate and determined with an atomic absorption spectrophotometer. Potassium, P, and micronutrients (Fe, Mn, Zn, Cu, and B) were extracted with the Mehlich 3 extractant using a 1:10 soil-solution ratio and determined with inductively coupled plasma spectrophotometer. The ECEC was computed as the sum of KCl-exchangeable Al and bases. The percentage of Al saturation was calculated in relation to ECEC. The total carbon and nitrogen were determined by combustion with LECO CN 2000 automatic analyzer (LECO Corp., St. Joseph, MI).

Fig. 1. Sample locations in northern and central Mozambique and AEZ.

Soil Mineralogy

The clay minerals were determined with X-ray diffraction methods (Moore et al., 1989). The air-dried soil was ground to pass a 2-mm sieve, put in 50-mL centrifuge tube with approximately 30 mL of water, and centrifuged at 13,500 g to remove soluble salts. The supernatant was discarded. The operation was repeated twice. The clay fraction was obtained by centrifuging at approximately 75.5 g, and the supernatant liquid decanted to a separate tube, which was centrifuged at 30,215 g. This operation was repeated until enough clay was obtained for analysis. The concentrated fine clay was placed in a glass slide and dried at room temperature for 24 h. X-ray diffraction was conducted with Siemens D-500 and Scintag PAD V automated diffractometer, at $0.03\ 2\theta^\circ$ ($20^\circ/\text{min}$ with Cu K α radiation).

P Sorption Curves

P sorption was determined by the Fox and Kamprath (1970) procedure. Three grams of air-dried soil that passed a 2-mm sieve were equilibrated in 50-mL plastic centrifuge tubes with 30-mL KH_2PO_4 solution containing 0, 2.5, 5, 10, and 20 mg P per liter 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 and Fox, 1972). Two drops of toluene was added in each sample. Each P level was conducted in duplicate. The samples were shaken horizontally in a reciprocal shaker for a 30-min period twice daily for 6 days and centrifuged at 30,215 g for 10 min and filtered. P in the supernatant solution was determined with the ammonium molybdo-phosphate-complex method (Olsen and Sommers, 1982). The P remaining in the solution was

Fig. 2. Particle size distribution of selected Mozambique topsoils (0–15 cm).

plotted against P sorbed, and a comparison of P sorption capacity was conducted by interpolating the amount of P needed to obtain 0.2 mg L^{-1} in the soil solution. Grouping of soils was made according to the intervals proposed by Juo and Fox (1977).

Statistical Analyses

Several statistical analyses were performed using various procedures provided by the Statistical Analysis Systems computer package (SAS Institute, 1997). Comparisons among soils were made with analysis of variance using the general linear model procedure.

RESULTS AND DISCUSSION

Particle Size Distribution and Mineralogy

Soil texture analysis indicates that most of the soils fall in the loamy sand, sandy loam, and sandy clay loam classes. The median of sand, silt,

and clay fractions was 67%, 12.1%, and 19.2%, respectively. The clay content ranged from 2.8% to 47.3% (Fig. 2, Table 1). Only 2 samples contained 40% or more clay, and 17% of the samples contained less than 10% clay. The silt/clay ratio of topsoil was relatively high. 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 less weathered soils (Ribeiro, 1976). Overall, the topsoil has lower clay content than subsurface layers, which suggests clay eluviation (Whittig, 1959).

X-ray analysis indicated some differences and similarities in the types of clay (Fig. 3). Most of the soils exhibited a high reflection intensity from spacing near 7.2 and 3.6 Å, which corresponds to kaolinite (Brindley and Brown, 1980). The samples showed some smectitic properties such as shrink and swell with wetting. However, the intensity of the peak in the range 16.9 to 19.1 Å was weak

TABLE 1
Means of soil properties of four agriculturally important agroecological zones of Mozambique, 2004 sampling

AEZ	Chemical properties									Particle size		
	pH	ECEC	Ca	Mg	K	Na	Al	Fe	Mn	Sand	Silt	Clay
	----- cmol _c kg ⁻¹ -----							--mgkg ⁻¹ --		----- % -----		
10	5.5	2.38	2.33	0.68	0.38	0.41	0.25	0.29	0.74	68.8	1.1	15.1
4	5.8	3.88	3.50	0.78	0.45	0.42	0.38	0.48	0.71	65.7	0.9	19.9
7	6.0	4.83	4.16	1.39	0.35	0.42	0.18	0.46	0.94	64.8	0.6	23.3
8	6.3	5.38	4.34	1.23	0.67	0.51	0.28	0.40	0.84	66.1	1.1	18.7

Fig. 3. X-ray diffractograms of surface soils (0–15 cm). Note: symbols in the figure indicate K-kaolinite and I-illite.

(Fig. 3). The common accessory minerals in most of the soils were hydroxides, oxyhydroxides, and oxides of Fe and Al. There is evidence of hematite- α - Fe_2O_3 (red color) goethite- α - FeOOH (yellow brown) and gibbsite-Al $(\text{OH})_3$, which correspond to reflection intensities in the regions 2.3 to 2.5 Å, 4.1 to 4.9 Å, and 4.7 to 4.85 Å, respectively. Traces of illite appeared in some samples (Fig. 3). There was a consistent weak peak near 10 Å in the soil from Manica (AEZ 4).

Soil Acidity

The pH in water varied considerably among sample sites. The range was from 4.4 to 7.8 (Fig. 4). The median was 6.0, the S.D. was 0.53, and the coefficient of variation was 8.9. Considering a soil pH between 5.0 and 5.5 as strongly acidic and below 5.0 extremely acidic, 12.9% of the samples were in the “strongly” and “extremely acidic” categories. These soils are likely to cause Al and Mn toxicity or Ca and Mg deficiency if planted to acid sensitive species such as cotton and certain varieties of sorghum and soybean. Approximately 76% of the samples were within adequate levels of pH (5.5–6.5), and 11.3% of the samples have pH greater than 6.5 and less than 7.8 (Fig. 4). The soils with a high pH are likely to have micro-nutrient deficiencies in Zn and Fe.

The delta pH of the topsoil, the difference of pH in KCl and pH in H_2O ($\text{pH}_{\text{KCl}} - \text{pH}_{\text{H}_2\text{O}}$), was significantly negative (< -0.5). In the topsoil, the KCl depressed overall pH by approximately 1.0 unit (Fig. 4), suggesting that these soils have net negative charge and are cation exchangers (Uehara and Gillman, 1981). In the subsurface layer (15–30 cm), 43% of the soil samples had a pH higher than the upper layers (data not shown).

The percentage of Al saturation of topsoil varied from 1.4% to 58.3%. Fifteen percent of

the samples contained more than 10% Al saturation (Fig. 5). In extremely acidic soils with a pH less than 4.5, the Al saturation was about 15%. Assuming 10% of Al saturation as a critical level for most sensitive crops, several soils are likely to limit plant growth due to Al toxicity or Ca and Mg deficiency. The soils with probable acidity limitations were mainly found in high elevation regions.

The relationship between pH and extractable Al was best described by a nonlinear regression (Fig. 5). The coefficient of regression indicated that 68% of the variation of extractable Al could be predicted from soil pH. Other studies report a similar, curvilinear-type relationship between extractable Al and pH (Kamprath, 1970; Coleman and Thomas, 1967).

Fig. 4. The relationship between pH in H_2O and in KCl of topsoil (0–15 cm).

Fig. 5. The relationship between KCl-extractable Al and soil pH.

Soil OM

Soil OM ranged from 0.4% to 5.0%. The median was 2.1%, and about 47.5% of the samples had low to very low level. Roughly 46% of the samples were within the medium range (2.0%–4.0%, Fig. 6). Only 5.5% of the samples had 4.0% or more OM. As expected, the amount of both total carbon and total nitrogen decreased with depth. In the surface layer, the range was from 0.39% to 5.7% organic matter, and the median was 2.1% organic matter. In the subsurface layer, the range was from 0.39% to 1.7%, and the median was 1.4%. Regression analysis of total carbon and total nitrogen indicated a positive relationship (Fig. 6). In the surface layer, 81% of the variation of total carbon can be attributed to the organic nitrogen. An analysis the relationship between clay content and OM showed no statistically significant correlation, possibly due to low clay content in these soils. Most of the samples have less than 20% clay.

Cation Exchangeable Capacity

The median ECEC was $5.0 \text{ cmol}_c \text{ kg}^{-1}$ and ranged from 0.4 to $14.5 \text{ cmol}_c \text{ kg}^{-1}$ (Fig. 7). Seventy-five percent of the samples had less than $7.5 \text{ cmol}_c \text{ kg}^{-1}$, the minimum level for adequate exchange capacity according to the Instituto de Investigação Agrária de Moçambique (IIAM, formerly INIA) soil fertility capability classification system. Therefore, in general, these soils have between low and moderate fertility capability. Other investigators, however, have proposed $4 \text{ cmol}_c \text{ kg}^{-1}$ as measured with unbuffered

salt as the upper limit of low cation exchange capacity (Lopes and Cox, 1977).

In an attempt to evaluate the relationship between ECEC and soil OM, pH in H_2O , percent clay, percent silt, and extractable Al, a stepwise multiple regression analysis was performed. The analysis indicated that OM and pH were statistically significantly correlated with ECEC at the 0.5 level of probability. Fifty percent of the observed variability of ECEC could be explained by OM content, and 64% of the variability could be explained by soil pH alone. The regression analysis did not identify clay or silt content as having a statistically significant contribution to the variability of ECEC. Table 2 shows the mean of soil properties according to FAO soil legend and by AEZ (Carta de Solos de Moçambique, 1996; Zonas Agroecológicas de Moçambique, 1980). The grouping by major soil type according FAO soil legend suggests inconsistent results when compared with the corresponding USDA Soil Taxonomy. The obvious reason seems to be the lack of site-specific data in preparing the FAO Soil Map. Soil mapping for the FAO legend took place during the civil war when access to soil samples was impossible, consequently initial maps were based on inadequate satellite imagery in many areas rather than on field assessment with sample collection and analysis. The Rhodic Ferrasols, for example, should be somewhat analogous to Oxisols and Ultisols of the US Soil Taxonomy, yet the ECEC/100 g clay values were as high as 54.4, which are values so high that they usually

Fig. 6. The relationship between total C and total N of surface and subsurface layers.

associated with soils with substantial 2:1 clays and thus were obviously misclassified.

These results point out the need for a thorough countrywide assessment and mapping of the soil resources based on laboratory soil data and modern mapping techniques such as remote sensing and soil sampling and analysis. A quantitative soil classification system such as the soil taxonomy would also contribute to improved soil resource assessment and ultimately to improved food security.

Exchangeable Bases (Ca, Mg, and K) and Extractable P

Surveys and preliminary estimates of critical levels of macronutrients in Mozambique soils

are scarce or nonexistent. The studies that exist deal largely with N and P. Table 2 has been used for interpreting soil exchangeable bases (Eschwiler, 1986). Figure 7 shows the frequency distribution of exchangeable bases and extractable P of the surveyed soils.

The median of extractable Ca was 3.5 $\text{cmol}_c \text{kg}^{-1}$, and the range was from 0.1 to 10.2 $\text{cmol}_c \text{kg}^{-1}$. Approximately 21.3% of the samples were below the "adequate" level of 4.0 $\text{cmol}_c \text{kg}^{-1}$. Extractable Mg ranged from 0.1 to 3.2 $\text{cmol}_c \text{kg}^{-1}$. The median was 0.7. Assuming 0.5 $\text{cmol}_c \text{kg}^{-1}$ as a lower limit of Mg adequate level, roughly 72% of the samples were within the "adequate" range. With regard to K, the minimum level was 0.2, and the maximum was 1.7.

Fig. 7. Frequency distribution of soil cations in the topsoil.

TABLE 2
Means of selected soil properties of topsoil (0–15 cm)

FAO map units	pH	OM, %	Clay, %	ECEC (cmol _c kg ⁻¹)	ECEC/100 g clay
Rhodic Ferralsols	5.7	2.5	19.8	5.2	54.4
Lithosols	5.5	1.8	15.2	4.0	26.6
Ferric Luvisols	6.3	2.3	21.3	6.4	37.0
Lithosols-Luvisols	6.3	1.9	21.4	7.0	39.2
Orthic Ferralsols	6.0	2.1	23.3	6.5	33.6

The median was 0.41 cmol_c kg⁻¹. It seems that K is present in adequate levels. A frequency distribution of Ca, K, Mg, and ECEC is shown in Fig. 7.

A comparison of soil nutrients by AEZ shows that the AEZ 10 in the central region is the most depleted of soil nutrients. The total P did not exceed 0.5 mg kg⁻¹, and the levels of Ca and Mg were less than 2.3 and 0.7 cmol_c kg⁻¹, respectively. In general, the AEZ 4, 7, and 8 contained low total P but moderate levels of Ca and Mg (Fig. 8, Table 1).

Micronutrients (Zn, Cu, Mn, Fe, and B)

Micronutrients are not part of IIAM's soil routine analysis. Thus, the analysis given here provides one of the first estimates of micronutrient status (Fig. 9). There was no information or established critical levels of micronutrients. The

comparisons of micronutrient analyses performed in this survey were based on the criteria proposed by Lindsay and Cox (1985) used in many countries in tropical regions (Table 4). The principle and methods used in extracting cations (Table 4) are somewhat comparable to Mehlich 3.

Zinc

Soil zinc ranged from 0.27 to 4.15 mg kg⁻¹. The median was 0.96 mg kg⁻¹. Roughly 10% of the samples had less than 0.5 mg kg⁻¹. Wear and Sommer (1948) considered 29 mg kg⁻¹ extracted with 0.05 M HCl + 0.05 M H₂SO₄ as a critical level. However, others have observed maize zinc-deficiency symptoms in a soil with between 0.2 and 0.5 mg L⁻¹ obtained with 0.04 M acetic acid extracting solution and from 0.5 to 0.9 mg kg⁻¹ with 0.1 M HCl. A similar range of Zn

TABLE 3
Soil property groupings, Instituto Nacional de Investigação Agronómica

Soil properties	Levels				
	Very low	Low	Medium	High	Very high
OM, %	<1.0	1.0–2.0	2.0–4.0	>4	—
N, %	—	0 < 0.1	0.1–0.2	>0.2	—
P, mg kg ⁻¹	—	0–5.0	5.0–10	10–15	>15
K, cmol _c kg ⁻¹					
Sandy soils, (<10% clay)	0 < 0.05	0.05–0.1	0.1–0.4	0.4–0.7	>0.7
Clay soils, (>40% clay)	0 < 0.2	0.2–0.4	0.4–1.2	1.2–2.0	>2.0
Other soils	0 < 0.1	0.1–0.2	0.2–0.4	0.4–0.8	>0.8
Ca, cmol _c kg ⁻¹					
Clay soils	0 < 2.0	2.0–5.0	5.0–10.0	10–20	>20
Other soils	0 < 0.5	0.5–2.0	2.0–4.0	4.0–6.0	>6
Mg, cmol _c kg ⁻¹					
Clay soils	0 < 0.2	0.2–0.5	0.5–1.0	1.0–2.0	>2.0
Sandy soils	0 < 0.3	0.3–1.0	1.0–3.0	3.0–6.0	>6.0
Na, cmol _c kg ⁻¹	0 < 0.1	0.1–0.3	0.3–0.7	0.7–2.0	>2.0
CEC, pH 7 cmol _c kg ⁻¹	0 < 3	3.0–7.5	7.5–15	15–30	>30
Base saturation, (%)	0 < 20	20–40	40–60	60–80	80–100
pH in H ₂ O					
<4.5, Extremely acid			6.1–6.5, Slightly acid		
4.5–4.0, Very strongly acid			6.6–7.3, Neutral		
5.6–6.0, Acid			7.4–7.8, Slightly alkaline		

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CEC indicates cation exchange capacity.

critical level was proposed by Lindsay and Cox (1985). It is generally believed that pH and OM are correlated with Zn availability. In our study, the amount of Zn did not significantly decrease with an increase of OM or soil acidity, which suggests that other factors besides OM and pH control the availability of Zn in these soils. In general, Zn levels seem adequate, but AEZ 4 and 7 giving the lowest levels (Fig. 9).

Copper

The overall median of copper (Cu) was 2.8 mg kg^{-1} . The range was from 0.63 to 22 mg kg^{-1} . There were differences in Cu content among AEZ. Agroecological zone 10 seemed to contain substantially higher Cu content when

compared with AEZ 8 (Fig. 9). The reasons of such differences might be associated with the soil types. Several of the sampled sites in AEZ 10 were from lithic soils.

Manganese

Soils with low pH may lead to Mn toxicity in crops. Studies conducted elsewhere have indicated that Ca deficiency may be induced with high soil Mn. In Mozambique, there are no studies indicating Mn problem in acid soil. Soil measurement indicates slight variation of soil Mn content among AEZ. Agroecological zone 7 has a slightly higher Mn content (1235 mg kg^{-1}) than other AEZ. An attempt to relate Mn content and soil pH shows no statistically

Fig. 8. Soil cations and ECEC of four AEZ of Mozambique.

Fig. 9. Soil micronutrient contents of four AEZ of Mozambique.

significant correlation. The overall median of Mn content was 1015 mg kg⁻¹, and the range was from 27 to 2470 mg kg⁻¹.

Iron

The iron content varied significantly among soils. The S.D. was 50. The range was from 38.4 to 279 mg kg⁻¹. The median was 116 mg kg⁻¹. There are presently no studies that have been

conducted in Mozambique that relate crop performance and Fe availability. Lindsay and Cox (1985) suggest 0.4 to 10 mg kg⁻¹ as a critical level. Assuming 10 mg kg⁻¹ as lower limit of critical level, all samples have sufficient Fe.

Boron

The median level of B in surveyed soils was 16.0 mg kg⁻¹. The range was from 1.81 to 35.5

TABLE 4

Summary of soil extracting solutions, shaking times, and ranges of critical levels for micronutrients used in many countries in tropical regions

Micronutrient	Extracting solutions	Soil/ solution ratio	Time of shaking	Range of critical level (mg kg ⁻¹)
Iron	DTPA, NH ₄ OAC, HCl, NaHCO ₃ , EDTA, NH ₄ F, and Na Citrate	1:2 and 1:40	10 min to 2 h	0.4–10
Manganese	DTPA, NH ₄ OAC, HCl, NaHCO ₃ , EDTA, NH ₄ F, H ₂ SO ₄ , and Na Citrate	1:2 and 1:20	5 min to 2 h	1–20
Zinc	DTPA, NH ₄ OAC, HCl, NaHCO ₃ , EDTA, NH ₄ F, KCl, and H ₂ SO ₄	1:2 and 1:20	5 min to 3 h	0.5–10
Copper	DTPA, NH ₄ OAC, HCl, NaHCO ₃ , EDTA, and NH ₄ F.	1:2 and 1:20	5 min to 2 h	0.2–10
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 min to 16 h	0.2–2

Source: Lindsay and Cox (1985).
DTPA indicates diethylenetriamine pentaacetic acid.

mg kg⁻¹. Boron deficiency might occur in a soil with a high percentage of OM or in soil of light texture. Neither case was found at sample sites, which suggests that B availability in these soils might not be a problem.

Phosphorous Sorption

The P sorption curves indicate that these soils have low (10–100 mg P per kilogram of soil) to medium (100–500 mg P per kilogram of soil) sorption capacity according to Juo and Fox's (1977) grouping (Fig. 10). The results show little displacement of the curves to the right at 0 P added, which indicates that these soils have low P. The amount needed to attain 0.2 µg mL⁻¹ in the equilibrated solution, a level considered adequate for normal plant growth (Fox and Kamprath, 1970) ranged from approximately 200 to 400 mg kg⁻¹. The Orthic Ferrasols (Fr) and Ferric Luvisols (Lf) sorbed the most P probably as a result of the moderate to high clay percentage, 28.9 and 15.5, respectively, and their highly weathered condition.

Comparison of Soil Properties Among Four AEZ

Agroecological zones represent important regions for food production and economic development. According to the IIAM (formerly INIA), Mozambique has 10 AEZ. A comparison among the zones shows some differences and similarities. Major differences exist in crop and cropping systems among the four AEZs selected for this study. Cotton, cassava, and groundnut are

the major crops in AEZ 7 and 8 in the northern provinces of Nampula and Cabo-Delgado, whereas in the central Mozambique (AEZs 4 and 10), maize and millet are traditionally cultivated by small-scale farmers.

Statistical analysis of soil macronutrients (Ca, Mg, K, and Na) and micronutrients (Zn, Mn, and Fe) indicated no statistical differences among the four AEZ. There was slight variation in soil pH and extractable Al.

Agroecological zone 8, situated in northern Mozambique, seems to have relatively better soil fertility capability compared with other regions. The ECEC, clay percentage, organic carbon, and pH in this region were generally higher than in the other regions. Extractable Ca ranged from 0.9 to 9.1 cmol_c kg⁻¹, and the median was 3.2 cmol_c kg⁻¹. Soil Mg ranged from 0.3 to 3.2 cmol_c kg⁻¹. The median was 0.6 cmol_c kg⁻¹. Assuming 1.0 cmol_c kg⁻¹ is a medium level (according IIAM's soil fertility capability classification), 7 of 13 samples in this region are below the medium category. Potassium level was within the adequate range. The range was from 0.1 to 1.7 cmol_c kg⁻¹, and the median was 0.4 cmol_c kg⁻¹.

Agroecological zone 10, in Manica province, was characterized by relatively more acidic conditions, together with low ECEC, but slightly higher OM than the AEZ 7 and 8. Differences were also observed with regard to the P sorption capacity. Generally, AEZ 4 revealed higher P sorption capacity. The obvious reason seems to be the high reactivity

Fig. 10. Phosphorus sorption curves of selected topsoils of four agroecological zones of Mozambique.

of the soils in this region. The comparison of X-ray diffractograms indicates high reflection intensities of these soils in the regions 2.3 to 2.5, 4.1 to 4.9, and 4.7 to 4.85 Å (Fig. 3), which corresponds to hydroxides, oxyhydroxides, and oxides of Fe and Al. Thus, this region seems to have higher Fe and Al content than region 8.

Predicting Fertilizer Needs for Maize with NuMaSS and PDSS

In agriculture, decision aids have proven to be very useful tools for predicting crop yield, plant growth, or fertilizer needs. In this study, soil nutrient requirement was predicted with computer software (NuMaSS and PDSS). The NuMaSS and PDSS are innovative approaches of predicting nitrogen, P, and potassium needs. The N module is based on Stanford equation that takes into account crop removal and soil site-specific information (soil nutrient condition, crop residual, and manure application). The estimation of P needs takes into account soil reactivity toward fertilizer P added, the crop requirement, placement factors, and the application method.

The prediction of N and P requirements indicates clearly that most of the soils in Mozambique are deficient. The range of N fertilization needs for a target yield of 4000 kg ha⁻¹ for maize ranged from 1.46 to 250 kg ha⁻¹ in more depleted areas. The median was 164 kg N ha⁻¹, which is substantially high for Mozambican farmers' with limited resources. The P needs ranged from 3.8 to 13.9 kg ha⁻¹. The median is 13.1 kg ha⁻¹. The results of the prediction of crop nutrient requirements show no consistent difference of fertilizer needs among AEZ. However, the N and P needs seem to be correlated with the clay content.

CONCLUSIONS

Several previous field surveys have indicated that soil fertility is a fundamental problem to food production in Mozambique. However, there are very few studies that provide the necessary quantitative data indicating which nutrients are deficient and where, and which would enable site-specific soil nutrient management. Our study suggests that most of the soils have low ECEC, which is probably because of the kaolinitic mineralogy, which was identified in many of the surveyed soils. Soil acidity in the high rainfall, high elevation region is likely to limit crop production. In those areas with low pH, soil P was much lower, probably due to the

high P sorption capacity. X-ray diffractograms indicate kaolinite and oxides and hydroxides of Fe and Al as the predominant clay minerals of these soils. Such materials strongly sorb P, which is of significant importance in controlling P availability. A comparison of soil properties belonging to different FAO categories shows little differences; probably, this owes to insufficient and inadequate field surveys and data collection during the civil war. The difficulties found in the FAO grouping point to a need for a modern, systematic survey of the soil resources of Mozambique.

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