African Crop Science Journal, Vol. 11. No. 4, pp. 245-257, 2003
Printed in Uganda. All rights reserved

ISSN 1021-9730/2003 $ 4.00

SOIL NUTRIENTS IN AGRO-ECOLOGICAL ZONES OF SWAZILAND

I. HAQUE and N.Z. LUPWAYI[1,2]
Faculty of Agriculture, University of Swaziland, Luyego, Swaziland
Current address: 105A, PCSIR Housing Society, Phase 1, Lahore 54590, Pakistan
[1]University of Malawi, Bunda College of Agriculture, Lilongwe, Malawi
[2]Current address: Agriculture and Agri-Food Canada, Box 29, Beaverlodge, Alberta, Canada T0H 0C0

(Received 14 March, 2000; accepted 30 July, 2003)

ABSTRACT

Per *capita* food production in Swaziland and other parts of sub-Saharan Africa will continue to decline unless soil fertility depletion is assessed. In light of this, total N, exchangeable bases, P fractions, available P, Cu, Zn, Mn and Fe contents were assessed in the 0-30 cm layers of soils in the highveld (>1500 m above sea level), middleveld (950-1500 m above sea level) and lowveld (<950 m above sea level) agro-ecological zones of Swaziland. Soils in the lowveld had significantly ($P<0.10$) higher Ca and Mg than other soils; and soils in the middleveld had significantly ($P<0.05$) lower N contents than other soils. Compared with critical levels, the soils were generally deficient in N, but had adequate Ca and Mg, especially in the lowveld. Potassium deficiency could also be expected in some low-CEC soils in the highveld. Highveld soils contained significantly more occluded P but less Al-P than other soils. Lowveld soils contained significantly more Ca-P but less Fe-P than other soils. Highveld soils contained less water-extractable P, resin-desorbed P and P fixation power than the other soils. Available P determined by nine different methods with their respective critical levels, showed that most of the soils were P-deficient according to four methods and P-sufficient according to the other five. Soils in the highveld contained significantly more Fe (both Fe-DTPA and Fe-HCl) than other soils, and soils in the middleveld had significantly more Zn-HCl than the other soils. Copper and Zn contents were generally highest in the lowveld, but the differences were not significantly different. Compared with critical levels, Cu and Fe contents seemed adequate, but Zn and Mn were deficient at some sites.

Key Words: Exchangeable cations, maize, micronutrients, P fractions, pumpkin

RÉSUMÉ

La production alimentaire par personne au Swaziland et autres parties de l'Afrique sub-Saharienne continuera a baisser à moins que la dimunition de la fertilité du sol est évaluée. En lumière de ceci, total N, bases échangeables, fractions de P, P disponible, contenus de Cu, Zn, Mn et Fe étaient évalués dans la couche de 0 – 30 cm de sol dans le haut veld (> 1500 m au dessus du niveau de mer), moyen veld (950 – 1500 m au dessus du niveau de mer) et bas veld (< 950 m au dessus du niveau de mer) des zones agro écologique de Swaziland. Les sols dans le bas veld avaient significativement ($P<0,10$) le Ca et Mg plus élevés que les autres sols ; et les sols dans le moyen veld avaient significativement ($P<0,05$) les contenus de N basses que les autres sols. Comparés aux niveaux critiques, les sols étaient généralement déficients en N, mais avaient le Ca et Mg adéquats, spécialement dans le bas veld. La déficience en potassium pourrait aussi être attendu dans les bas sols CEC dans le haut veld. Les sols de haut veld ont contenu significativement plus de P occlure mais moins de Al-P que les autres sols. Les sols de bas veld ont contenu significativement plus de Ca-P mais moins de Fe-P que les autres sols. Les sols de haut veld ont contenu moins de P en solution, P de résine fixé et une puissance de fixation de P que les autres sols. P disponibles déterminés par neuf méthodes différentes avec leurs niveaux critiques respectifs, ont montré que la majorité des sols était déficiente d'après quatre méthodes et P suffisant d'apres cinq autres. Les sols dans le haut veld ont contenu significativement plus de Fe (les deux Fe-DTPA et Fe-HCl) que les autres sols, et les sols dans le moyen veld avaient significativement plus de Zn-HCl que les autres sols. Les contenus en cuivre et Zn étaient généralement élevés dans le bas veld, mais les différences n'étaient pas significatives. Comparés aux niveaux critiques, les contenus en Cu et Fe ont semblé adéquats, mais le Zn et Mn étaient déficients aux certaines sites.

Mots Clés: Ions échangeables, maïs, micronutriments, fractions de P, citrouille

INTRODUCTION

Soil fertility depletion in smallholder farms is currently recognised as the fundamental biophysical cause of declining per *capita* food production in Africa (Sanchez *et al.*, 1997). In Swaziland, responses of various crops to N and other nutrients were demonstrated (Whitemarch, 1975; Jones, 1977, 1978 and 1979). But these responses were rarely linked to the levels of nutrients in the soil. Henry *et al.* (1992) correlated sugarcane yield responses to K with various soil K parameters and found that (Ca+Mg):K ratios of 15 and 26 for winter and summer cut cane, respectively, provided good separation between responsive and non-responsive soils. Henry and Shongwe (1995) reported that exchangeable and non-exchangeable K reserves in the heavy soils of the sugarcane-growing areas (lowveld, i.e., <950 m above sea level) of Swaziland were lower and less able to sustain K supply to plants on a long-term basis than the reserves in lighter soils. In the middleveld (950-1500 m above sea level), Ogwang (1988) reported that, for beef cattle requirements, native forage was deficient in crude protein and Mg contents, implying that the soils had low contents of N and Mg.

Phosphorus deficiency is, particularly critical in soils of sub-Saharan Africa (Jones and Wild, 1975; Buresh *et al.*, 1997). Soil P occurs in organic (Po) and various inorganic (Pi) fractions (pools), from which P is released into the soil solution at different rates (Buresh *et al.*, 1997). The P in soil solution, including P which is added to soil by fertiliser application, can be absorbed by plants and other soil biota and converted into organic P, or can be sorbed onto soil minerals. Depending on the strength of adsorption, the sorbed P can be released into soil solution again. Therefore, much of the soil P is unavailable for immediate plant consumption and many investigations have quantified the relationship between unavailable and available P. These studies include sequential extraction procedures (Chang and Jackson, 1957; Hedley *et al.*, 1982) used to estimate P availability from various fractions of soil P. The procedure of Chang and Jackson (1957) extracts Pi pools like calcium-P, aluminium-P and iron-P. In the Hedley *et al.* (1982) procedure, which includes Po pools, increasingly harsher treatments extract P fractions that are supposedly increasingly less available to plants (Beck and Sanchez, 1994). The extractants are anion-exchange resin for Pi, sodium bicarbonate ($NaHCO_3$) for Pi and Po, sodium hydroxide (NaOH) for Pi and Po, sodium hydroxide and sonication for Pi and Po, hydrochloric acid (HCl) for Pi and concentrated sulphuric acid (H_2SO_4) digestion for residual P (Hedley *et al.*, 1982; Beck and Sanchez, 1994). From a P management perspective, interpretation of all the P fractions in the Hedley procedure is difficult. Hence, Guo and Yost (1998) grouped the fractions of similar availability into three functional pools that can be assigned specific roles in P management, namely, readily available, reversibly available, and sparingly available P. The relative amounts of different P fractions in soils of Swaziland are still unclear.

Application of micronutrients to crops is usually not considered a priority in alleviating soil fertility problems in sub-Saharan Africa, probably because most small-scale farmers cannot even afford the fertilisers required to correct the more severe macronutrient (especially N and P) deficiencies. However, micronutrient deficiencies have been reported in field and pasture crops, and the latter can lead to deficiencies in livestock. Morris (1985) reported that established stands of *Pinus patula* responded significantly to application of Zn, Mn and Mo in the Usutu Forest of Swaziland. Ogwang (1988) analysed soil, forage and cattle liver and serum samples for mineral contents in the middleveld and related them to each other. For micronutrients, he concluded that cattle were likely to require supplementary Cu, Zn and Mn, but not Fe, implying that forage plants and, ultimately, soils, were not supplying adequate quantities of Cu, Zn and Mn.

The objective of this work was to assess the fertility level of soils in Swaziland by measuring the total N, exchangeable Ca, Mg, K and Na, P fractions and available P, and Cu, Zn, Mn and Fe contents of surface soils. We related the nutrient levels to other soil properties: pH, texture, organic matter, cation exchange capacity, base saturation, total Fe, total Al and extractable Al.

MATERIALS AND METHODS

Soil samples were collected from seven sites in the lowveld (<950 m above sea level), six sites in the middleveld (950-1500 m above sea level) and seven sites in the highveld (>1500 m above sea level) agro-ecological zones (AEZs) of Swaziland. The highveld is a mountainous region on the western side of Swaziland, with a temperate climate of warm, wet summers and dry winters. Forestry is the main industry in the highveld.

The middleveld is a hilly grassland region with a warm, sub-tropical climate ideal for cultivating various crops. It is the main agricultural area of Swaziland. The lowveld, a rolling lowland region further east, is the largest region covering about 40% of the country. It has near-tropical climate and is prone to drought, but sugarcane (*Saccharum* spp.), cotton (*Gossypium hirsutum*) and cattle are found in the region.

Mean annual temperatures range from 16°C in the highveld to 22°C in the lowveld, and annual rainfall ranges from 286 mm in the highveld to 508 mm in the lowveld, with most of the rain falling between October and March.

The sampling sites are presented on the map of Swaziland (Fig. 1) and their descriptions are listed in Table 1. Surface (0-30 cm depth) soil samples were collected from unfertilised fields growing mostly maize-beans-pumpkin (*Zea mays-Phaseolus vulgaris-Curcubita* spp.) intercrops in the highveld and lowveld, and mostly cotton in the lowveld. The samples were air-dried, ground and sieved to pass through a 2 mm mesh sieve.

Particle size was analysed using the pipette method, pH was measured in water (1:2.5 soil:water ratio), and organic C was measured by dry combustion. Total N was measured following Kjeldahl digestion. Exchangeable bases were determined by leaching with ammonium acetate at pH 7.0 and analysing the leachate for Ca^{++} or Mg^{++} by atomic absorption spectrophotometry (AAS) and K^+ or Na^+ by flame emission spectrophotometry. Cation exchange capacity (CEC) was analysed by measurement of the fixed ammonium after leaching of the exchangeable bases. The fixed ammonium was freed with NaCl and determined by automatic colorimetry. Base saturation (BS) was calculated as the sum of exchangeable bases divided by CEC. Iron and aluminium were extracted with the dithionate-citrate system buffered with sodium bicarbonate (Mehra and Jackson, 1960). Extractable aluminium was extracted with ammonium acetate at pH 4.8. Detailed descriptions of the methods used can be found in Tekalign *et al.* (1991a) and Kamara *et al.* (1992).

The methods for P analysis have been described in detail by Roche *et al.* (1980). Total P was measured after digesting the soil with perchloric acid and nitric acid. Organic P was estimated as the difference in 0.2N H_2SO_4-extractable P before and after ashing at 550°C (Bray and Kutz, 1945). Inorganic P was fractionated according to the method of Chang and Jackson (1957), i.e., extraction with NH_4F at pH 5.5 for aluminium-bound P (Al-P), with 0.1N NaOH for Fe-P, and with 0.5N H_2SO_4 for Ca-P. Occluded P was calculated as the difference between total P and the sum of fractionated inorganic P and organic P, i.e., occluded P = Total P - (Al-P + Fe-P + Ca-P + Organic P). In each case, extracted P was measured colorimetrically using the ascorbic acid-molybdate blue method (Watanabe and Olsen, 1965).

Several methods were used to measure available phosphorus. Olsen P was extracted with 0.5N $NaHCO_3$ at pH 8.5 (Olsen *et al.*, 1954), Dabin P was determined by extraction with 0.5N NH_4F and 0.5N $NaHCO_3$ at pH 8.5, Truog P by extraction with 0.002N H_2SO_4 (Truog, 1930), Bray (II) P by extraction with 0.03N NH_4F in 0.10N HCl (Bray and Kutz, 1945), Dalal P by extraction with 0.1N Na_2CO_3 (Dalal, 1973), and water-extractable P. The Larsen (L) value, which is an estimate of the "labile pool" of soil phosphorus, was estimated using radioactive isotope ^{32}P in pot experiments with *Agrostis* spp. (forage grasses), with the assumption that soil P which can be exchanged with the radioisotope represents the fraction of total P which is potentially available to plants. Labile P was also estimated by 48 h extraction with anion (F^-) exchange resins (Dalal, 1974) and an index of P availability, the Gachon index (Roche *et al.*, 1980) was calculated. The P fixing capacity of the soil was determined by shaking soil in a solution containing 100 µl P ml^{-1} and measuring the P remaining in solution. In each case, extracted P was measured colorimetrically using the ascorbic acid-molybdate blue method (Watanabe and Olsen, 1965).

Two methods were used to extract available Cu, Zn, Mn and Fe: (i) the diethylene triamine pentaacetic acid (DTPA) method [(0.005 M DTPA + 0.01 M $CaCl_2$ + 0.1 M $(HOCH_2CH_2)_3N$ adjusted to pH 7.3 with dilute HCl] and (ii) the 0.05 M HCl method. All the four cations in the extracts were determined by atomic absorption spectrophotometry. Detailed descriptions of these methods used can be found in Tekalign *et al.* (1991b).

Analysis of variance (ANOVA) (SYSTAT, 1992) was used to compare the nutrient contents

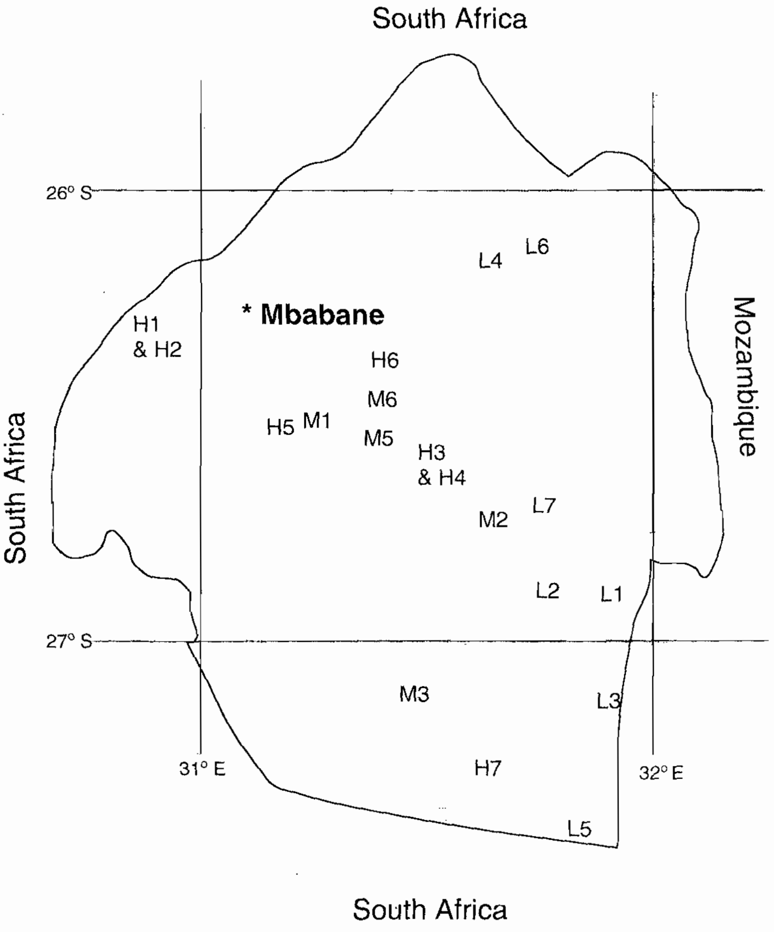

Figure 1. Map of Swaziland showing the sampling sites. H = highveld, M = middleveld and L = lowveld. The site names and other characteristics are listed in Table 1.

in the three AEZs, and means were separated by the least significant difference (LSD) test at P = 0.10. The seven or six sites within each AEZ were considered as replicates. To complement ANOVA results, principal component analysis (PCA) (SYSTAT, 1992) was also used to separate the sites according to their nutrient contents and other soil properties. Two- and three-component PCAs were conducted, but only two-component results are presented because they usually explained most of the variance.

RESULTS AND DISCUSSION

The highveld contained significantly more organic C, total Al and extractable Al, than the other AEZs, while the lowveld had significantly higher pH and CEC (Table 2). Differences in clay content, base saturation and total Fe were not significant.

The middleveld contained significantly less total N than the other AEZs. Although soil N measurements are often difficult to relate to crop requirements, 70 percent of the sites had low N contents (<0.2% N), and 25 percent medium N contents (0.2-0.5% N) according to most ratings (Landon, 1991) (Table 2). Therefore, N fertiliser may be required for high yields of most crops. The exchange complex was dominated by exchangeable Ca^{2+}, followed by exchangeable Mg^{2+}. The contents of both of these bases was significantly higher in the lowveld than in the other two AEZs. Exchangeable K^+ and Na^+ were minor components of the exchange complex, and their contents were not significantly different among the AEZs. The exchangeable Ca^{2+} and Mg^{2+} levels in all the soils were adequate in comparison with the critical limit of 0.4 cmol kg^{-1} soil (or 0.2 meq per 100 g soil) for both nutrients (Landon, 1991). However, with a critical level for K in the range 0.07 to 0.21 cmol kg^{-1} soil (Boyer, 1972; Tening *et al.*, 1995), some of these soils may require potassium fertilisers as 30 percent of them had K contents below 0.21 cmol kg^{-1}. In Swaziland, Henry *et al.* (1992) quoted K critical levels of 0.38 cmol kg^{-1} soil for intermediate-textured (30-40% clay) soils and 0.58 cmol kg^{-1} soil for heavy-textured (>40% clay) soils. With these critical levels, 50-60% of the soils are deficient in K (Table 2). The Na contents were all below sodic levels.

In principal component analysis of macronutrients contents (excluding P) and other soil

TABLE 1. Descriptions of the sampling sites in each agro-ecological zone

Site designation	Soil series	Agro-ecological zone (AEZ)	World Reference Base classification	Parent material
H1	Nduna A	Highveld[a]	Ferralsol	Granite
H2	Nduna B	Highveld	Ferralsol	Granite
H3	Sangweni A	Highveld	Ferralsol	Dolerite
H4	Sangweni B	Highveld	Nitisol/Cambisol	Dolerite
H5	Tateni	Highveld	Regosol	Granite
H6	Zombode	Highveld	Ferralsol	Granite
H7	Qolweni	Highveld	Ferralsol	Granite
M1	Pofane	Middleveld[b]	Arenosol/Leptosol	Granite/Colluvium
M2	Lesibovu	Middleveld	Luvisol	Aluvium/Colluvium
M3	Mooihoek	Middleveld	Nitisol/Ferralsol	Granite
M4	Qurrin	Middleveld	Unknown	Granodiorite
M5	Mdutshame	Middleveld	Nitisol	Granite
M6	Malkerns	Middleveld	Nitisol	Colluvium
L1	Somerling	Lowveld[c]	Leptosol/Cambisol	Basalt
L2	Rondspring	Lowveld	Cambisol	Basalt
L3	Canterbury	Lowveld	Vertisol	Basalt
L4	Bush Baby	Lowveld	Fluvisol	Alluvium
L5	Vimy	Lowveld	Vertisol	Basalt
L6	Zwide	Lowveld	Solonetz	Sandstone & shales
L7	Habelo	Lowveld	Solonetz	Sandstone & shales

[a]>1500 m above sea level; [b]950-1500 m above sea level; [c]<950 m above sea level

Source: Jones (1977, 1978, 1979)

properties listed in Table 2, principal component 1 (PC1) separated soils at four locations (L5, L3, L2 and H4) from soils at the rest of the sites (Fig. 2). These four sites had higher CEC, exchangeable bases, pH and clay than the other sites, and, except H4 (Sangweni B), they are located in the lowveld and derived from basalt parent material (Table 1). These results are in agreement with ANOVA results described above (Table 2). The locations separated by PC2 differed in organic C and total N contents, ranging from sites like L1 (Somerling) and H4 (Sangweni B), which had high C and N contents, to sites like L4 (Bushbaby) and L7 (Habelo), which had low C and N contents. Figure 2 shows that most of the sites with high C and N contents are located in the highveld, as the analysis of variance results also indicated. Therefore, these results show that soils in the highveld are likely to be more acidic, less clayey and have higher organic matter and organic N contents, but lower exchangeable base contents, than soils in the lowveld. Henry *et al.* (1992) also observed that most soils in the lowveld were base saturated. One reason for the high contents of basic cations in soils of the lowveld is probably their basic (basalt) parent material (Table 1).

The effects of the major cations on crop growth are often interlinked, i.e., the ratios of the nutrient contents are also important. Some ratios of nutrient contents are summarized in Table 2. The C:N ratio is an indication of the degree of humification of organic matter, with the equilibrium level considered to be 10:1 for temperate soils (Landon, 1991), but direct interpretation to crop nutrition is difficult to make. The lowveld had significantly lower C:N ratio than the other AEZs. The Ca:Mg ratios ranged from 1:1 to 3:1, and soils in the lowveld had significantly higher ratios than soils in the other AEZs. Landon (1991) quoted 3:1 to 4:1 as the optimum range of Ca:Mg ratios for most crops, with lower ratios inhibiting P uptake, and 1:1 as the lowest acceptable limit because Ca availability is reduced at lower ratios. The Ca:Mg balance in these soils could be inhibitory to P

TABLE 2. Nitrogen and exchangeable base contents of the soils and the percentages of soils that had contents below critical levels. Other soil properties are also listed

Soil property	Highveld	Middleveld	Lowveld	Critical level of nutrient or ratio	Sites with nutrient or ratio below critical level (%)
Clay (%)	39.7a[a]	28.2a	41.3a	-	-
Organic C (%)	2.48a	1.33b	1.66b	-	-
Total N (%)	0.21a	0.11b	0.17a	0.2[b]	70
C:N ratio	12.0a	12.8a	9.7b	-	-
pH	5.2b	5.7b	7.2a	-	-
CEC (cmol [+] kg^{-1})	14.3ab	8.7b	31.1a	-	-
BS (%)	50.0a	58.7a	79.9a	-	-
Total Fe (μg g^{-1})	52.8a	28.7a	48.8a	-	-
Total Al (μg g^{-1})	132.5a	93.9b	100.8b	-	-
Extractable Al (μg g^{-1})	0.18a	0.06b	0.01b	-	-
Exch. Ca (cmol kg^{-1})	9.7b	5.3b	35.2a	0.4[c]	0
Exch. Mg (cmol kg^{-1})	5.3b	3.1b	13.8a	0.4[b]	0
Exch. K (cmol kg^{-1})	0.50a	0.41a	0.77a	0.38-0.58[d]	50-60
Exch. Na (cmol kg^{-1})	0.09a	0.11a	0.28a	≯15[b]	0
Ca:Mg ratio	1.8b	1.6b	2.4a	1:1-3:1[b]	80
K:Mg ratio	0.15a	0.14a	0.10a	≯1:1[b]	0
Exch. K % (EPP)	3.5a	4.7a	3.3a	2[e]	25
Exch. Na % (ESP)	1.0a	1.4a	1.1a	≯15[b]	0

[a]Means followed by the same letter within a row are not significantly different at P=0.10 using the least significant difference (lsd) test; [b]Landon (1991); [c]This ratio in cmol K and Mg per kg soil is equal to the 2:1 ratio quoted by Landon (1991) in meq K and Mg 100 g^{-1} soil; [d]Henry *et al.* (1992); [e]Boyer (1972). > means that the quoted nutrient content or ratio is the upper limit; EPP = exchangeable potassium percentages; ESP = exchangeable sodium percentage

uptake by plants as about 80 percent of them had Ca:Mg ratios between 1:1 and 3:1. The K:Mg ratios were all below the 1:1 ratio (or 2:1 ratio if the units of K and Mg are meq per 100 g soil) above which Mg uptake may be inhibited (Landon, 1991). Seventy-five percent of the soils had exchangeable potassium percentage (EPP) values above the critical 2% below which K deficiency may be a problem (Boyer, 1972). All the exchangeable sodium percentages (ESPs) were below 15%, and so none of the soils were sodic even though soils at L5 (Vimy) and L7 (Habelo) were classified as Solonetz.

Quantities of P fractions were in the following order in the highveld and middleveld: occluded P > organic P > Fe-P > Al-P > Ca-P (Table 3). The order in the lowveld was: occluded P > organic P > Ca-P > Al-P > Fe-P. Although soils in the highveld contained significantly more exchangeable Al than other soils (Table 2), they contained less Al-P, as a percentage of total P (Table 3). Soils in the lowveld had significantly higher Ca-P, but lower Fe-P, than soils in the other AEZs.

Principal component analysis of the contents of soil P fractions, available P and the other soil properties (excluding macronutrients) (Table 2) revealed that Al-P was higher at L6 (Zwide), L4 (Bushbaby), L3 (Canterbury), L5 (Vimy) and M6 (Malkerns) than at the other sites (Fig. 3). All these sites, except Malkerns, are located in the lowveld. These results confirm the ANOVA results although Al-P contents in the three agro-ecosystems were not significantly different (Table 2). Fe-P was higher and organic P lower at sites like M6 (Malkerns), M3 (Mooihoek), M5 (Mdutshame), H1 (Nduna A) and L6 (Zwide) (mostly in the highveld and middleveld) than at L5 (Vimy), L3 (Canterbury) and L2 (Rondspring) (Fig. 3). In Ethiopia, the distribution of inorganic P fractions in different soil types was found to be Ca-P > Fe-P > Al-P (organic P constituted about 41%, on average, of total P) (Tekalign and Haque, 1991a) and Fe-P > Al-P > Ca-P (Piccolo and Halluka, 1986).

The extracted P ranged from high amounts by the Dabin and Dalal methods to low by water extraction and the Truog method. There were

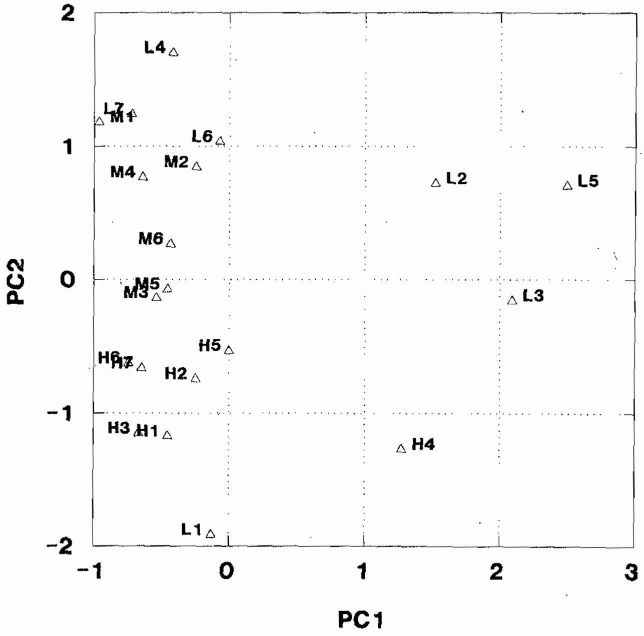

Figure 2. Ordination of the contents of N, exchangeable cations and other soil properties (see text) at different locations by principal component analysis (PCA). Along principal component 1 (PC1), soils at locations on the right-hand side of the figure had higher CEC, Ca, Mg, K, Na, pH and clay than soils at locations on the left-hand side. Along PC2, soils at locations at the bottom of the figure had higher organic C and total N contents than soils at locations at the top. PC1 explained 60% of the variance and PC2 explained 24% of the variance.

TABLE 3. Phosphorus fractions, contents of available P determined by different methods and the percentages of sites which had P contents below critical levels

Soil property	Highveld	Middleveld	Lowveld	Range of critical levels[a]	Sites with P contents below critical level (%)
Al-P (μg g^{-1})	13.1a[b]	21.0a	20.6a	-	-
Fe-P (μg g^{-1})	43.5a	43.5a	17.9b	-	-
Ca-P (μg g^{-1})	9.9b	12.3b	69.8a	-	-
Occluded P (μg g^{-1})	211.9a	113.5b	102.6b	-	-
Organic P (μg g^{-1})	80.9a	55.8a	98.4a	-	-
Al-P (% of total P)	4.1b	8.5a	7.7a	-	-
Fe-P (% of total P)	13.3a	16.6a	7.5b	-	-
Ca-P (% of total P)	2.7b	5.0b	21.3a	-	-
Occluded P (% of total P)	58.7a	39.7b	30.5b	-	-
Organic P (% of total P)	21.3a	30.3a	33.1a	-	-
Olsen P (μg g^{-1})	26.5a	47.7a	37.6a	5-8[c]	0
Dabin P (μg g^{-1})	59.6a	63.3a	48.4a	20-50	15-40
Truog P (μg g^{-1})	3.7a	5.4a	18.6a	8-15	75-85
Bray (II) P (μg g^{-1})	4.7a	12.9a	32.8a	10-20	60-70
Dalal P (μg g^{-1})	50.4a	49.7a	32.6a	50-140	60-100
Water extractable P (μg g^{-1})	0.07b	0.25ab	0.64a	0.2-0.5	55-85
L value (μg g^{-1})	28.1a	29.4a	38.5a	15-30	20-45
Gachon index	1.9a	4.8a	13.5a	2-5	35-60
Resin desorption	6.5b	17.2ab	27.2a	10-17	40-65
P fixation (P remaining in solution)	1353.6a	520.8b	686.3b	-	-

[a]From Roche *et al.* (1980), unless stated otherwise; [b]means followed by the same letter within a row are not significantly different at P = 0.10; [c]Landon (1991) and Tekalign and Haque (1991b)

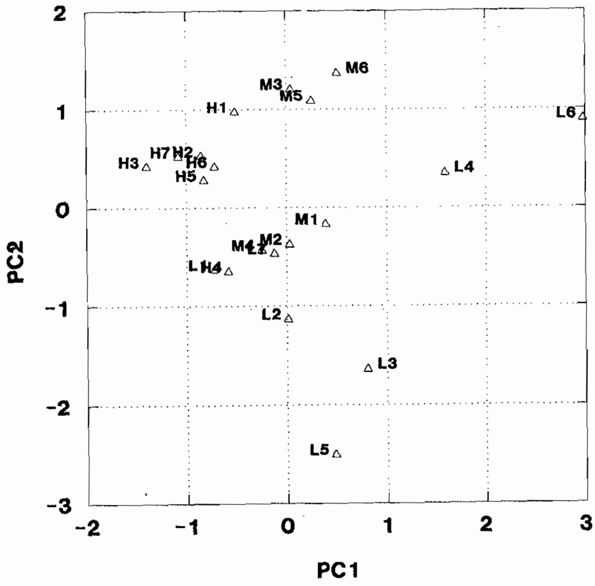

Figure 3. Ordination of the contents of soil P and other soil properties at different locations by principal component analysis (PCA). Along principal component 1 (PC1), soils at locations on the right-hand side of the figure had higher resin P, Gachon index, Bray P, Truog P and Al-P than soils at locations on the left-hand side. Along PC2, soils at locations at the top of the figure had higher Fe-P and Dalal P but lower CEC and organic P than soils at locations at the bottom. PC1 explained 32% of the variance and PC2 explained 23% of the variance.

mostly no significant differences between the AEZs in the amounts or indices of available P, except water extractable P, resin P and P fixation power, which were all significantly lower in the highveld than in the other AEZs (Table 3). However, PCA (Fig. 3) showed that the sites (mostly from the lowveld: L6, L4, L3, L5 and M6) that had higher Al-P than the others also had higher resin P, Gachon index, Bray P and Truog P. Soils in the lowveld also had higher contents of exchangeable bases than those in the highveld (see above). PCA also showed that Dalal P was higher at sites that also had higher Fe-P and lower organic P (like M6, M3, M5, and L6) than at L5, L3 and L2.

After analysing available P results from about 480 tropical soils from around the world, Roche *et al.* (1980) suggested different critical levels depending on soil type (Table 3). According to these critical levels, Truog P, Bray (II) P, Dalal P and water-extractable P were below critical levels in the majority of the soils; but Dabin P, L value, Gachon index and resin P showed that P was adequate in most of the soils (Table 3). Landon (1991) quoted a critical level of 5 µg g^{-1} for Olsen P. In Ethiopia, Olsen P gave the highest correlation with P uptake and dry matter yield of *Macroptilium lathyroides* and the critical level was found to be 8.5 µg g^{-1} (Tekalign and Haque, 1991b). Olsen P levels in Swaziland were all greater than this critical level. This wide variation between methods emphasizes the need for calibration of the P contents with growth of crops grown in Swaziland. In greenhouse experiments with maize, Henry *et al.* (1993) showed that the Truog method (extraction with 0.02 N H_2SO_4) was the best suited for soils in Swaziland and South Africa. Our Truog-P results show that most (75-85%) of these soils were P deficient (Table 3).

DTPA extracted more of each micronutrient than HCl (Table 4) and, apart from Zn, the extracted amounts were highly correlated. The order of DTPA-extractable micronutrients was Fe > Mn > Cu > Zn in the highveld and middleveld, but lowveld soils contained more Mn than Fe. The order for HCl-extractable micronutrients was Mn > Fe > Cu > Zn in the highveld and lowveld, but the middleveld contained slightly more Zn than Cu. There were no significant differences between AEZs in DTPA-extractable or HCl-extractable Cu. All the soils had adequate Cu content according to published critical levels of 0.2 µg g^{-1} for DTPA-extractable Cu (Follet and Lindsay, 1970) and 0.09-1.06 µg g^{-1} for HCl (0.1M)-extractable Cu (Landon, 1991) (Table 4). The amounts of DTPA-extractable Zn (0.6-20.3 µg g^{-1}) were mostly (at 45 to 100 percent of the sites) above the critical limit range of 0.5-1.5 µg g^{-1} (Landon, 1991; Sharma and Lal, 1993, Tiwari and Dwivedi, 1993; Akram *et al.*, 1995), and the middleveld contained more Zn than the other AEZs. However, 60% of the sites had Zn-HCl contents below the critical 1 µg g^{-1} quoted by Lopez (1975). There were no significant

TABLE 4. Micronutrient contents and the percentages of soils that had contents below critical levels

Soil property	Highveld	Middleveld	Lowveld	Critical level of nutrient	Sites with nutrient contents below critical level (%)
Cu-DTPA (µg g^{-1})	6.0a[a]	4.8a	10.1a	0.2[b]	0
Zn-DTPA (µg g^{-1})	1.9a	4.7a	1.6a	0.5-1.5[c]	45-100
Mn-DTPA (µg g^{-1})	49.8a	25.9a	44.9a	2.9-3.3[d]	0
Fe-DTPA (µg g^{-1})	88.5a	43.9b	22.9b	2.5-4.5[e]	0-5
Cu-HCl (µg g^{-1})	1.4a	1.8a	2.3a	0.09-1.06[f]	0
Zn-HCl (µg g^{-1})	0.9b	2.4a	0.8b	1[g]	60
Mn-HCl (µg g^{-1})	17.4a	12.7a	21.3a	5-9[e]	5-40
Fe-HCl (µg g^{-1})	11.1a	6.6ab	5.1b	-	-

[a] Means followed by the same letter within a row are not significantly different at P=0.10 using the least significant difference (lsd) test; [b] Follet and Lindsay (1970); [c] Landon (1991), Sharma and Lal (1993), Tiwari and Dwivedi (1993), Akram *et al.* (1995); [d] Bansal and Nayyar (1989 and 1990); [e] Landon (1991); [f] for 0.1M HCl (Landon, 1991); [g] Lopez (1975)

differences between AEZs in Mn contents. Critical levels of DTPA-extractable Mn were in the 2.9-3.3 μg g^{-1} range (Bansal and Nayyar, 1989 and 1990) and 5-9 μg g^{-1} for HCl-extractable Mn (Landon, 1991). None of the soils had DTPA-extractable Mn below critical limits and 5 to 40 percent of them had HCl-extractable Mn below the critical limits (Table 4). Similarly, only 0 to 5 percent of the soils had DTPA-extractable Fe below the 2.5-4.5 μg g^{-1} range of critical levels quoted by Landon (1991). We were unable to find critical levels for HCl-Fe in literature. The Fe contents were significantly higher in the highveld than in the other AEZs. Therefore, the micronutrient contents of these soils seem to be adequate for crop production, although much depends on the crop. Jones (1979) reviewed responses of crops to micronutrients at Malkerns (middleveld) and reported that most responses to Cu, Zn and Mn (Fe was not reviewed) were insignificant.

Principal component analysis of the contents of micronutrients and the other soil properties (not macronutrients) (Table 2) showed that soils at L1 (Somerling), H4 (Sangweni B), L2 (Rondspring), L3 (Canterbury) and L5 (Vimy) had more Cu-DTPA, Mn-HCl, clay and Mn-DTPA than soils in the other locations (PC1 axis in Fig. 4). These sites (except Sangweni) are all located in the lowveld and the soils are derived from basalt parent material (Table 1). In this instance, PCA has revealed differences that were not significantly different with analysis of variance. Soils in the lowveld were also found to have higher contents of exchangeable bases and available P (see above) than soils in the highveld or middleveld. PCA results also showed that soils at sites like L1 (Somerling), H5 (Tateni), and H4 (Sangweni B) had more Fe-DTPA than soils at L5 (Vimy), L3 (Canterbury) and L2 (Rondspring) (PC2 axis in Fig. 4), i.e., most of the lowveld sites had lower Fe contents than other sites. However, as noted above (Table 4), the Fe content was adequate in at least 95% of all the sites.

CONCLUSIONS

This study has shown that most soils of Swaziland probably have low N but adequate Ca and Mg contents. Potassium may be deficient in some of the low pH and low CEC soils in the highveld. Without correlations with crop uptake and yields in our results, it is difficult to determine which of the methods for evaluating available P are better than others. According to the Truog method, which has been suggested to be the best indicator of available P for maize in Swaziland soils most of the soils are P deficient. The contents of Cu and

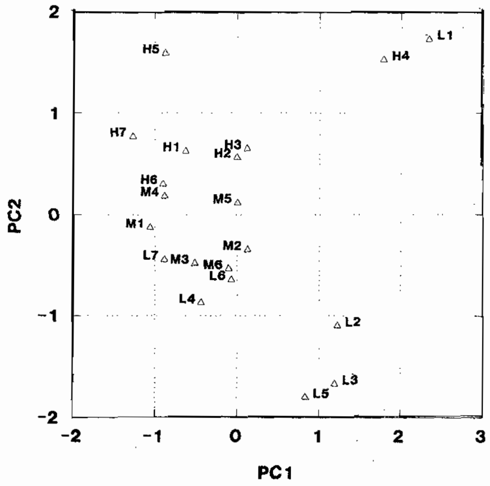

Figure 4. Ordination of the contents of micronutrients and other soil properties at different locations by principal component analysis (PCA). Along principal component 1 (PC1), soils at locations on the right-hand side of the figure had more Cu-DTPA, Mn-HCl, clay and Mn-DTPA but less Fe-HCl than soils at locations on the left-hand side. Along PC2, soils at locations at the bottom of the figure had higher pH but lower Fe-DTPA than soils at locations at the top. PC1 explained 37% of the variance and PC2 explained 19% of the variance.

Fe are also probably adequate, but Zn and Mn may be deficient in some cases. However, since the soils were mostly classified using critical levels derived from outside Swaziland, calibration of the nutrient levels with crops grown in Swaziland is recommended.

ACKNOWLEDGEMENTS

We thank Dr M.J. Jones and Mr J. Morris for assistance in collecting soil samples. We also thank the World Phosphate Institute for financial support and for P analysis.

REFERENCES

Akram, M., Chaudhry, R.A., Ahmad, Z. and Haq, G.U. 1995. Predicting DTPA soil test zinc and associated rice response to applied zinc. *Communications in Soil Science and Plant Analysis* 26:259-268.

Bansal, R.L. and Nayyar, V.K. 1989. Critical level of Mn in Ustochrepts for predicting response of green gram (*Phaseolus aureus* L.) to manganese application. *Fertilizer Research* 21:7-11.

Bansal, R.L. and Nayyar, V.K. 1990. Critical manganese deficiency level for soybean grown in Ustochrepts. *Fertilizer Research* 25:153-157.

Beck, M.A. and Sanchez, P.A. 1994. Soil phosphorus fraction dynamics during 18 years of cultivation on a Typic Paleudult. *Soil Science* 34:1424-1431.

Boyer, J. 1972. Soil potassium. In: *Soils of the Humid Tropics.* Drosdoff, M. (Ed.), pp. 102-125. US National Academy of Sciences, Washington, DC., USA.

Bray, R.H. and Kurtz, L.T. 1945. Determination of total organic and available forms of phosphorus in soils. *Soil Science* 59:39-46.

Buresh, R.J., Smithson P.C. and Hellums, D.T. 1997. Building soil phosphorus capital in Africa. In: *Replenishing Soil Fertility in Africa.* Buresh, R.J., Sanchez, P.A. and Calhoun, F. (Eds.), pp. 111-149. SSSA Special Publication Number 51, Soil Science Society of America and American Society of Agronomy, Madison, WI., USA.

Chang, S.C. and Jackson, M.L. 1957. Fractionation of soil phosphorus. *Soil Science* 84:133-144.

Dalal, R.C. 1973. Estimation of available phosphorus in soils by extraction with sodium hydroxide-sodium carbonate solution. *Journal of Australian Institute of Agricultural Science* 39:142-143.

Follet, R.H. and Lindsay, W.L. 1970. Profile distribution of zinc, iron, manganese and copper in Colorado soils. Tech. Bull. 110. Colorado State University Experimental Station, Fort Collins, CO., USA.

Guo, F. and Yost, R.S. 1998. Partitioning soil phosphorus into three discrete pools of differing availability. *Soil Science* 163:822-833.

Haque, I., Lupwayi, N.Z. and Ssali, H. 1999. Agronomic evaluation of unacidulated and partially acidulated Minjingu and Chilembwe phosphate rocks for clover production in Ethiopia. *European Journal of Agronomy* 10:37-47.

Hedley, M.J., Stewart, J.W.B and Chauhan, B.S. 1982. Changes inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Science Society of America Journal* 46:970-976.

Henry, P.C., Meyer, J.H, Wood R.A. and Smith, M.F. 1992. Improving the prediction of potassium requirements in base saturated lowveld soils. In: *Proceedings of the Annual Congress of the South African Sugar Technologists Association* 66:54-58.

Henry, P.C., Shongwe, G. and Bhembe, V. 1993. Evaluation of four soil phosphate extractants and phosphorus fixation in soils from Swaziland sugarcane areas. *Proceedings of the Annual Congress of the South African Sugar Technologists Association* 67:60-65.

Henry, P.C. and Shongwe, G. 1995. Evaluation of potassium availability in three major soil groups in the Swaziland sugarcane areas. *Proceedings of the Annual Congress of the South African Sugar Technologists Association no.* 69:50-54.

Jones, M.J. 1977. Summaries of work on soil fertility at Swaziland experimental sites. 2.

Nhlangano. *Research Report No. 16.* Malkerns Research Station, Malkerns, Swaziland.

Jones, M.J. 1978. Summaries of work on soil fertility at Swaziland experimental sites. 3. Lowveld Experimental Station, Big Bend. *Research Report No. 17.* Malkerns Research Station, Malkerns, Swaziland.

Jones, M.J. 1979. Summaries of work on soil fertility at Swaziland experimental sites. 9. Magnesium, sulphur and micronutrients at Malkerns. *Research Report No. 24.* Malkerns Research Station, Malkerns, Swaziland.

Jones, M.J. and Wild , A. 1975. *Soils of the West African Savanna.* Technical Bulletin No. 55 of the Commonwealth Bureaux of Soils. Commonwealth Agricultural Bureaux, Farnham Royal, Slough, UK.

Kamara, C.S., Haque, I. and Saka, A.R. 1992. *Soil Physics Manual.* Plant Science Division Working Document No. B12 (Revised). International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia.

Landon, J.R. (Ed.). 1991. *Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics.* Longman Scientific & Technical, Essex, England.

Lopez, A.S. 1975. A survey of the fertility status of soils under cerrado vegetation in Brazil. M.S. Thesis, North Carolina State University, Raleigh, NC., USA.

Mehra, O.P. and Jackson, M.L. 1960. Iron oxides removal from soils and clays by dithionate-citrate system buffered by sodium bicarbonate. *Clays and Clay Minerals* 7:317-327.

Morris, A.R. 1985. Responses to applications of nitrogen, phosphorus, potassium, boron, sulphur, lime and trace elements in established stands of *Pinus patula. Forest Research Report No. 81*. Usutu Pulp Company Limited, Swaziland.

Ogwang, B.H. 1988. The mineral status of soil, forage and cattle tissues in the middleveld of Swaziland. *Experimental Agriculture* 24:177-182.

Olsen, S.R., Cole, C.V., Watanabe, F.S. and Dean, L.A. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *USDA Circ. 939*, Washington, DC., USA.

Piccolo, A. and Halluka, G. 1986. Phosphorus status of some Ethiopian soils. *Tropical Agriculture* 63:137-142.

Roche, P, Griere, L., Babre, D., Calba, H. and Fallavier, P. 1980. *Phosphorus in Tropical Soils: Assessing Deficiency Levels and Phosphorus Requirements.* IMPHOS-World Phosphate Institute Scientific Publication No. 2. Paris, France.

Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A.N., Mokwunye, A.U., Kwesiga, F.R., Ndiritu, C.G. and Woomer, P.L. 1997. Soil fertility replenishment in Africa: an investment. In: *Replenishing Soil Fertility in Africa.* Buresh, R.J., Sanchez, P.A. and Calhoun, F. (Eds.), pp. 1-46. SSSA Special Publication Number 51, Soil Science Society of America and American Society of Agronomy, Madison, WI.USA.

Sharma, S.K. and Lal, F. 1993. Estimation of critical limit of DTPA zinc for wheat in Pellusterts of southern Rajasthan. *Journal of Indian Society of Soil Science* 41:197-198.

SYSTAT. 1992. *SYSTAT for Windows: Statistics, Version 5 Edition.* SYSTAT, Inc., Evanston, Ill:nois, USA.

Tekalign, M. and Haque, I. 1991a. Phosphorus status of some Ethiopian soils. II. Forms and distribution of inorganic phosphates and their relation to available phosphorus. *Tropical Agriculture* 68:2-8.

Tekalign, M. and Haque, I. 1991b. Phosphorus status of some Ethiopian soils. III. Evaluation of soil test methods for available phosphorus. *Tropical Agriculture* 68:51-56.

Tekalign, T., Haque, I. and Aduayi. E.A. 1991. *Soil, Plant, Water, Fertilizer, Animal Manure and Compost Analysis.* Plant Science Division Working Document no. B13, International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia.

Tening, A.S., Tarawali, G. and Omueti, J.A.I. 1995. Critical potassium deficiency levels for a grass/legume pasture grown on soils of the humid zone of Nigeria. *Communications in Soil Science and Plant Analysis* 26:673-685.

Tiwari, K.N. and Dwivedi, B.S. 1993. Fertilizer zinc demands of corn as influenced by native zinc supply in Udic Ustochrepts of Uttar

Pradesh. *Journal of Indian* ***Society*** *of Soil Science* 41:793-796.

Truog, E. 1930. The determination of readily available phosphorus of soils. *Journal of American Society of Agronomy* 22:874-882.

Watanabe, F.S. and Olsen, S.R. 1965. Test of ascorbic acid method for determining phosphorus by water and sodium bicarbonate extracts from soil. *Soil Science Society of America Procedings* 29:677-678.

Whitemarch, A.R.T. 1975. Veld and pasture research in Swaziland. Miscellaneous Report No. 108. Malkerns Research Station, Malkerns, Swaziland.