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Full Length Research Paper

Delineation of management zones by classification of soil physico-chemical properties in the Northern Savanna of Nigeria

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This study was designed to identify properties that explained variability in soils of farmers' fields in Kaya, within the northern Guinea savanna benchmark and group the soils on the basis of the identified properties. Ridge and furrow soil samples from farmers' fields were analyzed for determination of physical and chemical properties. Principal component analysis of soil properties extracted and characterized factors that described the overall soil fertility variation; potential fertility, available phosphorus, organic matter, acidity and sand-silt. Component scores were computed and used for cluster analysis. Five soil cluster groups corresponding to potential management zones were identified. In Cluster A soils were sandy, low in phosphorus, organic matter and exchangeable bases. Cluster B was characterized by acidic and silty soils with low exchangeable bases, organic matter and phosphorus. Soils within Cluster C were acidic, sandy in texture, with low exchangeable bases, phosphorus and organic matter. In the single member Cluster D, the soil was rich in organic matter and phosphorus. Cluster E soils were high in exchangeable bases and organic matter but low in phosphorus. The identified soil clusters are delineated management zones and this determines their suitability or otherwise for specific agronomic management practices.

Key words: Cluster analysis, northern guinea savanna, principal component analysis.

INTRODUCTION

The northern Guinea savanna (NGS) is one of the most intensified farming areas in Nigeria (IITA, 1994). Particular features such as daily solar radiation of 270 to 350 cal cm^{-2} day^{-1} during the growing season, and 440 cal cm^{-2} day^{-1} in the dry months; between 900 to 1200 mm of reliable, well distributed rainfall, and lower night temperatures promote dry matter accumulation and partitioning leading to a higher harvest index and yield (Jagtap, 1995: FAO, 1978: Kassam et al., 1975). As such, the NGS has the potential to be one of the most productive regions of the world. In reality, food production within the zone is grossly below the world average. For a cereal crop like maize, while the average yield in developed countries can reach up to 8.6 t ha^{-1}, and the average yield worldwide is estimated at 2.8 t ha^{-1}, average production per hectare is just a little above one tonne in the savanna region of Nigeria (FAO, 2003; Ofor et al., 2009). The International Institute of Tropical Agriculture (IITA) has adopted an agroecoregional approach to research on nutrient resource management since the early 1990s. The West African moist savanna zone has been divided into different agroecoregions, each with their distinctive length of growing periods (Vanlauwe et al., 2002). Within each agroecozone, benchmark sites have been identified in which most of the IITA resource management research is concentrated (EPHTA, 1996).

The benchmark site of the NGS is located in northern Nigeria. The NGS benchmark is chosen to represent the larger ecoregional zone and it is 6.5% of the NGS zone and approximately 100 by 200 km. The site, which is one of the six benchmarks of the Ecoregional Program for the Humid and Sub humid Tropics of sub-Saharan Africa

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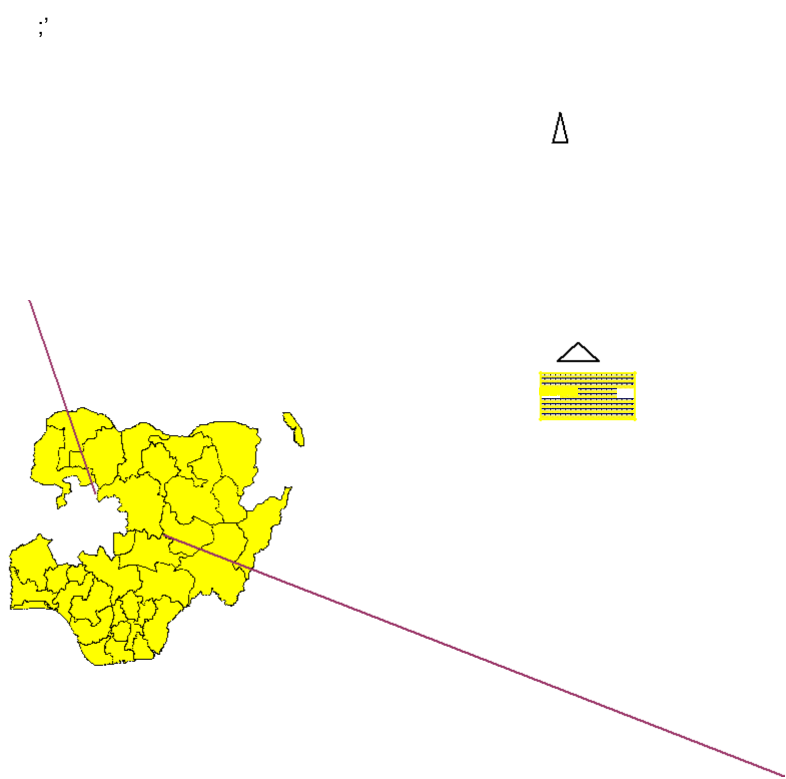

Figure 1. Map of Kaduna state showing the location of Kaya, with map of Nigeria inset.

(EPHTA), has all the gradients observed for the total agroecological zone to allow extrapolation to the total zone (Brader, 1998). Farmers' fields located within benchmark sites are used in testing new technologies subsequent to on-station trials, before they may be recommended to farmers. However, results from such trials have often given varying results despite similar management practices. This has been partly attributed to spatial variability of soil properties across farmers' fields (Okogun et al., 2004). These soil properties interact in complex manners to affect crop yield. Soil variation in a small area affects the planning and design of agronomic experiments and the interpretation of the experimental results as well as the formulation of practical recommendations (Kosaki and Juo, 1989). Knowledge of the variability of soil properties is essential to selecting as well as effectively applying management decisions in the field (Shukla et al., 2004).

One of the better options for on-farm agricultural experimentation could be the classification of soils on farmers' fields into groups on the basis of soil properties. Specific nutrient management recommendations could then be targeted to specific groups.

The present study was undertaken to:

(1) Extract and identify important soil variables that define most of the variability within farmers' fields; and
(2) Delineate soil nutrient management zones by the combined usage of Principal Component Analysis (PCA) and cluster analysis.

MATERIALS AND METHODS

The study area

The study area was located on 41 farmers' fields at Kaya village (7 13'E, 11 13'N) in the NGS IITA benchmark site (Figure 1).

The length of growing period is about 150 days occurring between May and October. The climate of the area is marked by distinct wet and dry seasons with a mean annual rainfall of 1060 mm (Agbenin, 2003). Averages of rainfall and temperature data for the location are presented in Figure 2.

Soil sampling and analysis

Farm size in the study area was between 1 to 3 ha (Manyong et al., 2001). Before the fields were prepared in June 1998, two bulk soil samples were collected from each of the fields with a 6 cm soil auger in the following manner. Twenty soil cores were taken each from the ridges and the furrows of the previous cropping season at

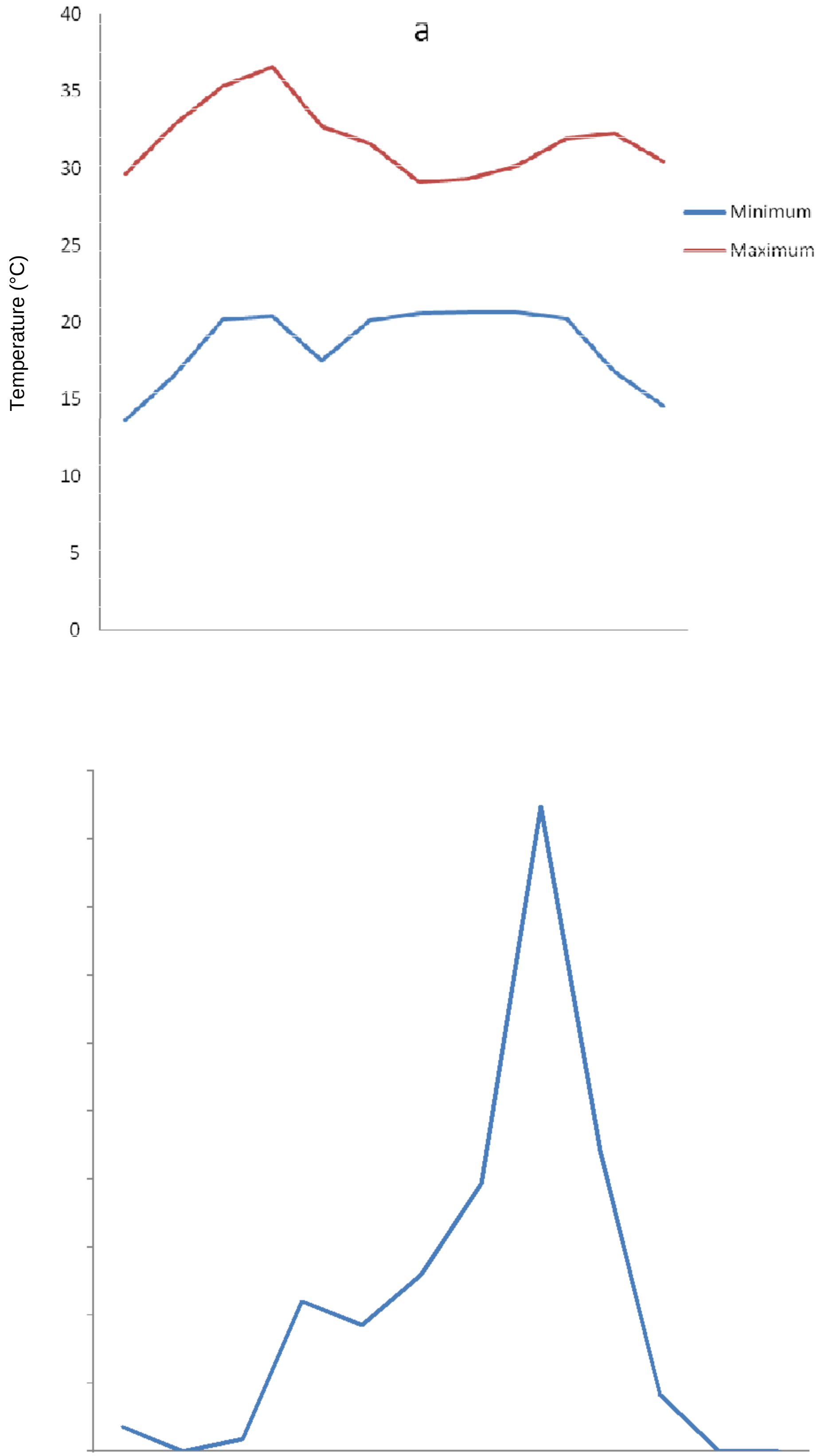

Figure 2. Ombrothermic diagrams of long-term (1968-1997) mean monthly (a) minimum and maximum temperatures and (b) monthly precipitation at Kaya, Nigeria.

Table 1. Chemical and physical soil properties of farmers' fields (0-15 cm) at Kaya, Nigeria.

Variable	Ridge			Furrow		
	Range	Mean	Standard deviation	Range	Mean	Standard deviation
Chemical characteristics						
Organic C (%)	0.47-1.12	0.7	0.17	0.34-1.15	0.6	0.16
Total N (%)	0.05-0.08	0.06	0.01	0.05-0.08	0.06	0.01
Olsen P (mg kg $^{-1}$)	1.0-51.7	8.6	9.07	1.0-37.0	5.9	6.12
Ca^{2+} (cmol kg $^{-1}$)	0.9-4.8	2.2	0.83	1.3-5.6	2.64	0.95
Mg^{2+} (cmol kg $^{-1}$)	0.2-1.9	0.65	0.29	0.4-2.4	0.95	0.35
K^{+} (cmol kg $^{-1}$)	0.1-0.8	0.25	0.12	0.2-0.8	0.37	0.13
Na^{+} (cmol kg $^{-1}$)	0.2-0.4	0.29	0.04	0.2-0.4	0.29	0.05
Mn^{+} (cmol kg $^{-1}$)	0.01-0.1	0.04	0.03	0.01-0.04	0.02	0.01
Exch. acidity (cmol kg $^{-1}$)	0.3-1.3	0.45	0.24	0.3-2.3	0.54	0.39
ECEC (cmol kg $^{-1}$)	1.8-8.2	3.84	1.16	3.1-9.1	4.79	1.33
pH (water)	4.9-6.6	5.6	0.42	3.9-6.3	5.3	0.49
Physical characteristics						
Sand (%)	35-65	46	7.04	31-57	44	6.81
Silt (%)	28-52	42	5.60	25-50	38	5.72
Clay (%)	7-25	12	3.61	11-30	18	4.69

a depth of 0 to 15 cm within a field and bulked together as either ridge soil or furrow soil. A sub-sample from each bulk sample was air-dried and ground to pass through a 2 mm sieve for physical and chemical analyses. Soil samples were analyzed for pH in water (1:1), organic carbon, total N, available phosphorus, exchangeable bases as well as particle size distribution using the routine procedures described by IITA (1979).

Statistical analysis

The mean, standard deviation (SD) and minimum-maximum values were calculated for measured soil properties. Principal component analysis (PCA) was computed to investigate soil variance and identify important variables to be used for further analyses. Principal component analysis creates new, uncorrelated variables from highly correlated soil properties (Jolliffe, 1986). The first principal component (PC) accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible. Since the units of the variables were not identical, the correlation matrix was used to calculate the PCs. In order to aid the interpretation of the PCs that are considered relevant, a varimax rotation was carried out on the PCs that were retained. Computation for PCA was performed using the SAS procedure FACTOR (SAS Institute, 1999). Component scores were computed for each of the soils in terms of the retained PCs, which were responsible for the soil variation in the study area. Component scores were weighted with unity and served for cluster analysis. Clustering is often enhanced by PCA. This is because the results of clustering are easily corrupted by the addition of "noise". Thus clustering can benefit from a pre-processing step of feature/variable selection or from a filtering or de-noising step as occurs in a PCA (Ben-Hur and Guyon, 2003). Soil classification procedure was performed using hierarchical cluster analysis technique. Ward's minimum variance method was used for hierarchal cluster analysis of soil data. The computation was carried out using the SAS procedure CLUSTER (SAS Institute, 1999).

Variables employed for PCA in this study included organic carbon (OC), total nitrogen (TN), available phosphorus (AP), exchangeable calcium (Ca), exchangeable magnesium (Mg), exchangeable potassium (K), exchangeable sodium (Na), exchangeable manganese (Mn), exchangeable acidity (ACID), effective cation exchange capacity (ECEC), pH in water (pH), sand (SAND), silt (SILT) and clay (CLAY). Ridge and furrow values of all measured properties were determined and written in suffix as F and R after the variable names, representing furrow and ridge respectively.

RESULTS AND DISCUSSION

Table 1 shows the summary statistics of the original data in terms of mean, range and standard deviation for each of the variables. The eigen values and the proportion of the total variance explained by each of the first five retained principal components derived from PCA is presented in Table 2. All together, the first five components explained over 70% of the total variation observed. Table 3 gives the rotated factor patterns or factor loadings for the retained five PCs.

For the first component (PC1) high loadings were represented by Mg_F, Mg_R, K_R, Ca_F, Ca_R, $ECEC_R$, $ECEC_F$, $CLAY_F$ and $CLAY_R$. These variables have to do with the exchangeable base status and cation exchange capacity of the soil and are relevant to the 'potential fertility' level of the soil.

The second component (PC2) gave high loadings for AP_F, AP_R, K_F, ACID $_F$, and Mn_R. This component can be readily interpreted as the 'available phosphorus' component, which is strongly influenced by the exchangeable acidity of the soil. Kosaki and Juo (1989) in their study of a derived savanna soil using PCA identifies PC1 as 'inherent fertility' dominated by Mg, sand, silt, Ca,

Table 2. Eigen values and proportion of variance to the total variance for the first five principal components.

Principal components	Eigenvalue	Proportion	Cumulative percentage
PC1	7.778	0.278	27.8
PC2	4.956	0.177	45.5
PC3	2.994	0.107	56.2
PC4	2.341	0.084	64.5
PC5	1.733	0.062	70.7

Table 3. Rotated factor loadings for the first five principal components (PC).

Variable	PC1	PC2	PC3	PC4	PC5
PH_F	-10	30	73	-3	-11
OC_F	-16	3	18	64	34
TN_F	-3	16	3	90	15
AP_F	-12	83	17	23	4
$SAND_F$	-43	1	1	-16	-79
$SILT_F$	-2	27	-5	15	85
$CLAY_F$	66	-34	4	5	10
CA_F	57	-7	67	17	29
MG_F	81	-20	34	5	23
K_F	24	76	5	31	-14
NA_F	32	4	1	23	-36
MN_F	-11	41	-66	-8	22
$ACID_F$	7	68	-12	2	21
$ECEC_F$	68	17	54	18	30
PH_R	35	-5	76	-4	-25
OC_R	32	11	3	76	8
TN_R	35	2	-11	84	4
AP_R	10	90	8	11	11
$SAND_R$	-35	-12	40	-35	-63
$SILT_R$	-3	15	-30	33	69
$CLAY_R$	73	1	-30	17	16
CA_R	76	19	43	20	-10
MG_R	89	-13	15	5	0
K_R	85	25	-6	-2	-8
NA_R	40	22	-15	-3	1
MN_R	-8	67	-37	-20	23
$ACID_R$	4	17	-23	22	4
$ECEC_R$	88	17	28	20	-7

K and clay and PC2 as 'available P' dominated by P and Ca. From Ishida et al. (2003) paddy soil fields' study using PCA; large contributions to PC1 are derived from phosphate adsorption coefficients, CEC, Ca and Mg, while PC2 has high loadings for pH, base saturation percentages, Na and K. The differences between the studies indicate that soil property PCA results is dependent on specific soil forming processes and soil conditions, which are unique to a particular location (Jiang and Thelen, 2004). The third component was highly related to OC_F, OC_R, TN_R and TN_F and may be termed the 'organic matter' component. The fourth component had high positive loadings for pH_F, pH_R, Ca_F and high negative loading for Mn_F. This may be described as the 'acidity 'component of the soil. The high positive loading for Ca_F and negative loading for Mn_F describes

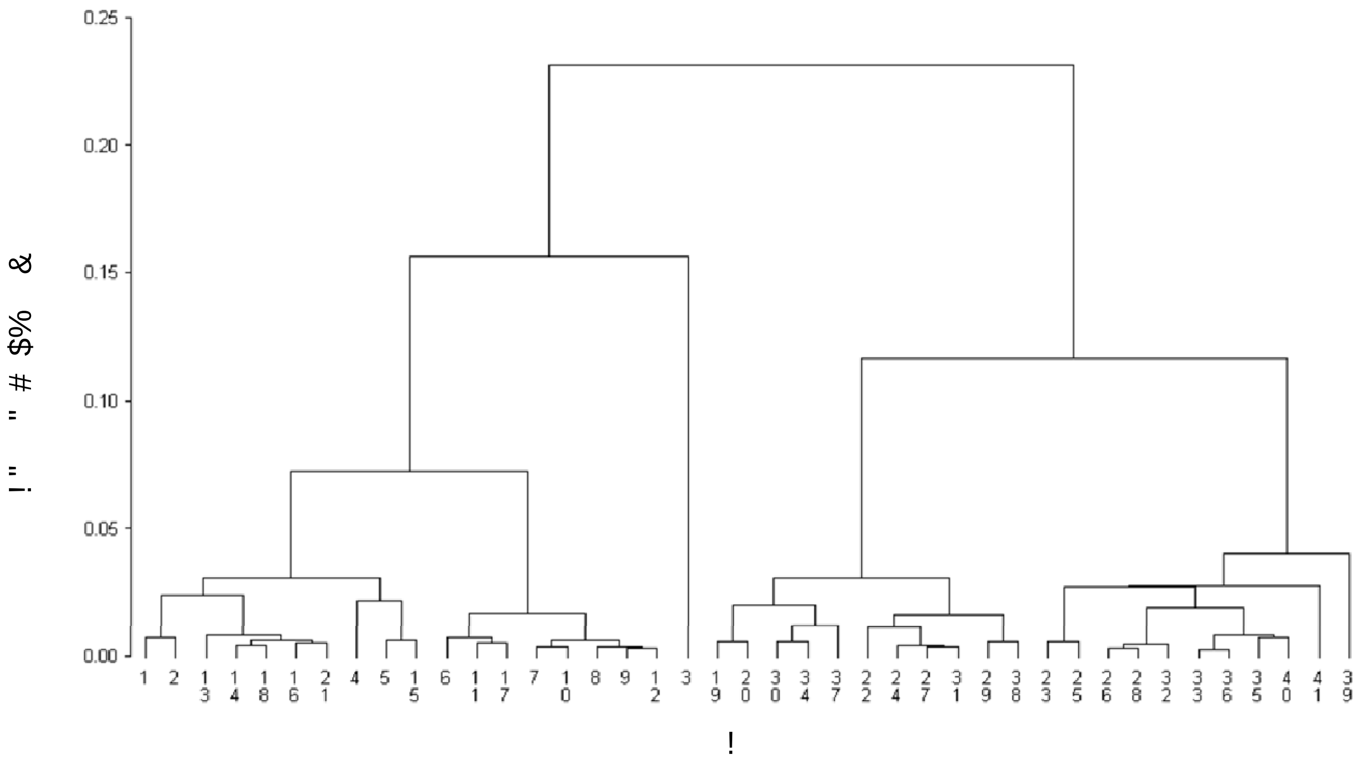

Figure 3. Dendogram of soil clusters from 41 farmers' fields in the northern Guinea savanna of Nigeria.

Table 4. Mean values of soil groups belonging to each cluster.

Cluster	No. of Members	Means				
		Potential fertility	Available phosphorus	Organic matter	Acidity	Sand-silt
A	14	-0.081	-0.254	-0.084	1.072	-0.206
B	12	-0.511	0.009	0.132	-0.528	0.691
C	11	-0.183	-0.046	-0.402	-0.783	-0.63
D	1	-0.021	4.864	1.351	0.675	0.5
E	3	2.756	-0.386	1.076	-0.294	-0.161

the relationship of the variables with soil pH. At high soil pH the concentration of manganese in soil solution is minimal but at low soil pH, manganese toxicity frequently occurs. Calcium availability is improved in soils with higher pH values and at high levels, may result in low solubility of manganese (Troeh and Thompson, 1993). The fifth component had high positive loadings for $SILT_F$ and $SILT_R$, and high negative loadings for $SAND_F$ and $SAND_R$. This component indicates fine soil particles that formed as a result of the physical weathering of rocks and are relevant to the basic soil properties such as available pore space and the capacity to store and release plant nutrients (Troeh and Thompson, 1993). This component may therefore be termed 'sand-silt'.

Component scores for the five named components were computed for all fields and used for cluster analysis. Five final clusters were recognized based on a subjective examination (disjoint level at 0.05) of the dendrogram (Figure 3). The mean values for the attributes of the soil clusters are given in Table 4. These clusters revealed the inherent differences between the soils. Cluster A was the largest group, distinguished primarily by a high mean value for 'acidity' component. These soils were sandy, moderately acidic and highly P deficient. Organic matter and ECEC levels in such soils were low. Cluster B showed a high value for 'sand-silt' component and a very low value for 'potential fertility' component. These soils had considerably high silt content, were low in exchangeable bases, organic matter and available P. The soils within Cluster C were defined by negative values for all the components being infertile and characterized by low ECEC, exchangeable bases, available P and organic matter values. Clusters D and E were distinguished from the others by high mean values for 'Organic matter'. In addition, Cluster D, a single member group was characterized by high ‘available phosphorus’, ‘acidity’ and ‘sand-silt’ values. Soils within Cluster E were high in exchangeable bases but low in available P.

Soil fertility replenishment is a critical factor with which farmers in the West African moist savanna zone have to cope to sustain and increase crop production (Nwoke et al., 2004). With the increasing intensification of agriculture on land currently used for traditional farming, a thorough knowledge of the soil as a resource including information on distribution, potential and constraints of major soils is needed so as to design the most appropriate soil management systems (Kang and Tripathi, 1992).

Most soil clusters were deficient in nitrogen, with low levels of organic matter, exchangeable bases and phosphorus. The considerably high silt level of these soils has previously been reported (Møberg and Esu, 1991) and is attributed to the Aeolian origin of the parent material (Vanlauwe et al., 2002). The low levels of soil organic carbon and ECEC observed in most clusters are in consonance with values obtained by Møberg and Esu (1991) for a range of Nigerian savanna soils. Soils within cluster E with high ‘potential fertility’ value may likely be a result of being formed from parent materials with higher exchangeable bases and clay. For the soil cluster D, the unusually very high P value of the single member soil cannot be ascribed solely to fertilizer application but may be due to the underlying parent material. The lack of adequate levels of major nutrients, notably N, P and exchangeable cations in most of the clusters indicate that crop production in these soils without addition of amendments will result in poor yields. Apart from the need for judicious use of chemical fertilizer to supply plant nutrients, management strategies for these soils must incorporate organic resources such as crop residues, prunings, cover crops and animal manure where available (Vanlauwe et al., 2002). Legume rotations and fallows are some identified practices that would support sustainable crop farming and productive soil management in the zone (Carsky et al., 2003). Slow release P sources such as phosphate rock may be tested on such soils for crop (especially legume) production. The high silt content of these soils makes them more prone to erosion and organic matter incorporation and maintenance of adequate plant cover will reduce topsoil loss.

Amounts of fertilizer added for good crop yield would vary with the cluster, with Cluster E for example requiring considerably lesser amounts than other soil clusters due to higher ECEC and organic matter levels. However, like other soil groups, this cluster would benefit from adequate organic matter management so as to ensure sustained use for crop production. In addition, soil quality would be much improved by soil conservation measures like conservation tillage (Salako, 2003).

In specifically designing management packages for each soil cluster, the type of crop to be grown, other management practices and relationship between crop yield and soil physico-chemical properties should be considered.

Conclusion

Soil variability and grouping of benchmark soils in the northern Guinea savanna of Nigeria was done using multivariate techniques. These results show that the soil potential fertility, available phosphorus, organic matter, acidity and sand-silt components are important factors that vary widely within the study area. Five clusters corresponding to soils with unique properties for the extracted soil factors makes it possible to target management practices suitable for each soil cluster , in other words a ‘cluster specific management’.

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