*Geo-Eco-Trop 1995, 19(1-4), 35-50*

# USE OF NUMERICAL METHODS IN DETERMINING SOIL FERTILITY AFFINITIES IN THREE CONTIGUOUS SAND DUNE FIELDS OF NW NIGERIA

## Utilisation de méthodes numériques dans la détermination des affinités quant à leur fertilité entre les sols de trois champs de dunes contigus du NW du Nigeria

B.A.RAJI., V.O.CHUDE* & I.E.ESU**

*RESUME*

*Soixante échantillons de sol superficiel ont été prélevés en douze sites différents et soumis à plusieurs types de classification: la taxonomie classique des sols et trois classifications numériques fondées respectivement, l'une sur les 21 propriétés mesurées ou appréciées sur le terrain et en laboratoire, la deuxième sur les seuls caractères de terrain et enfin, la troisième sur des propriétés mesurées en laboratoire et relatives à la fertilité. Selon la première classification, seuls se dégagent deux grands groupes : les* Haplustults *et les* Quartzopsamments. *Les classifications numériques, par contre, à leur niveau le moins élevé, ont abouti à quatre groupes, non compris deux sites isolés, faisant ressortir le rôle de caractères géographiques tels que le climat, le site topographique, l'épaisseur de la couverture sableuse et la nature de la roche sous-jacente. La valeur (value) de la couleur du sol sec se révèle être un bon indicateur de la fertilité. D'autre part, il existe peu de désaccord entre les différentes classifications, même en ce qui concerne celle fondée sur les caractères de terrain. Cette harmonie doit être attribuée à la richesse en substances nutritives et à la capacité d'échange qui sont prises en compte, même implicitement dans la classification non numérique. Celle-ci toutefois, de par ses groupes assez larges, est moins satisfaisante en ce qui concerne la fertilité, notamment en-deçà des valeurs critiques de certaines propriétés.*

*ABSTRACT:*

*Sixty sand dune surface soils from twelve sites were classified both by a non-numerical classification (Soil Taxonomy) and by three numerical classifications, based on (i) all 21 properties which were measured in the field and laboratory, (ii) on properties measured in the field (morphology) only, and (iii) on laboratory properties*

* Department of Soil Science, Institute for Agricultural Research, Ahmadu Bello University, Zaria, Nigeria

** Department of Soil Science , University of Calabar, Calabar, Nigeria

*related to soil fertility Two broad groups,* Haplustults *and* Quartzipsamments, *were obtained using Soil Taxonomy. However, using the numerical classifications, four main groups and 2 unattached soil sites were delineated at the lowest level and these show a pattern related to the geographical distribution, meso-relief, thickness and the underlying geology of the dunes. Comparison of the different classifications shows that there is broad agreement between them and between classifications based on different suite of properties. Even classification based on field properties only, showed close similarity to others. Results of this study also indicate a possibility of using colour value of dry soil as an index of soil fertility in the dune soils. The close similarity between the numerical and the non-numerical systems of classification may be attributed to the fact that properties which relate largely to nutrient status and exchange capacity of the soils, are those on which the numerical classification was based and these properties are nearly the same as those on which the non-numerical classification is also based. The nonnumerical classification however, gave broad groupings and therefore seems not to be totally satisfactory in defining fertility affinity in closely related soil series especially when absolute values of soil properties are below critical limits.*

## INTRODUCTION

Numerical taxonomy, originally used to quantitatively express phrenetic resemblance in biological sciences, has of recent been applied in soil science, especially in pedogenetic studies (RAYNER, 1966; MOORE *et al* 1972; GRIGAL & ARNEMAN, 1969; CIPRA *et al* 1976). There however, appear to be many situations where numerical methods could be applied profitably.

One of these is in the area of soil fertility studies (MOORE & RUSSEL, 1967; CHANG & CHEN, 1985). In methods currently in use to evalute fertility affinity between soils, emphases are placed either on homogeneous groupings in terms of selected few properties: diagnostic horizons and critical limits are used in soil taxonomy (Soil Survey Staff, 1994) or on one or few constraints to fertility capability classification (BUOL *et al.*, 1975; SANCHEZ *et al.*, 1982). These methods however, do not adequately indicate affinities between closely related soils, as obtainable at the level of soil series, of weakly developed or young soils (MOORE & RUSSELL, 1967; MATHAN *et al.*, 1994). This is because a meaningful grouping of these soils on either field observations or on a few selected properties is difficult, since these soils show little chemical variation within or between profiles (Soil Survey Staff,1975).

A number of fertility problems are reported for the sand dune soils occupying the northwestern part of Nigeria (FAO, 1969; RAJI, unpublished data). All the soils have been reported to be low in nutrient elements, such as nitrogen, phosphorus, exchangeable bases, organic matter, usually below the critical lower limits reported in literature (FAO, 1969; RAJI *et al.*, 1996). It is however, desirable that fertility affinities between members of this broad range of sand dune soils be adequately defined for proper fertilizer and fertility management

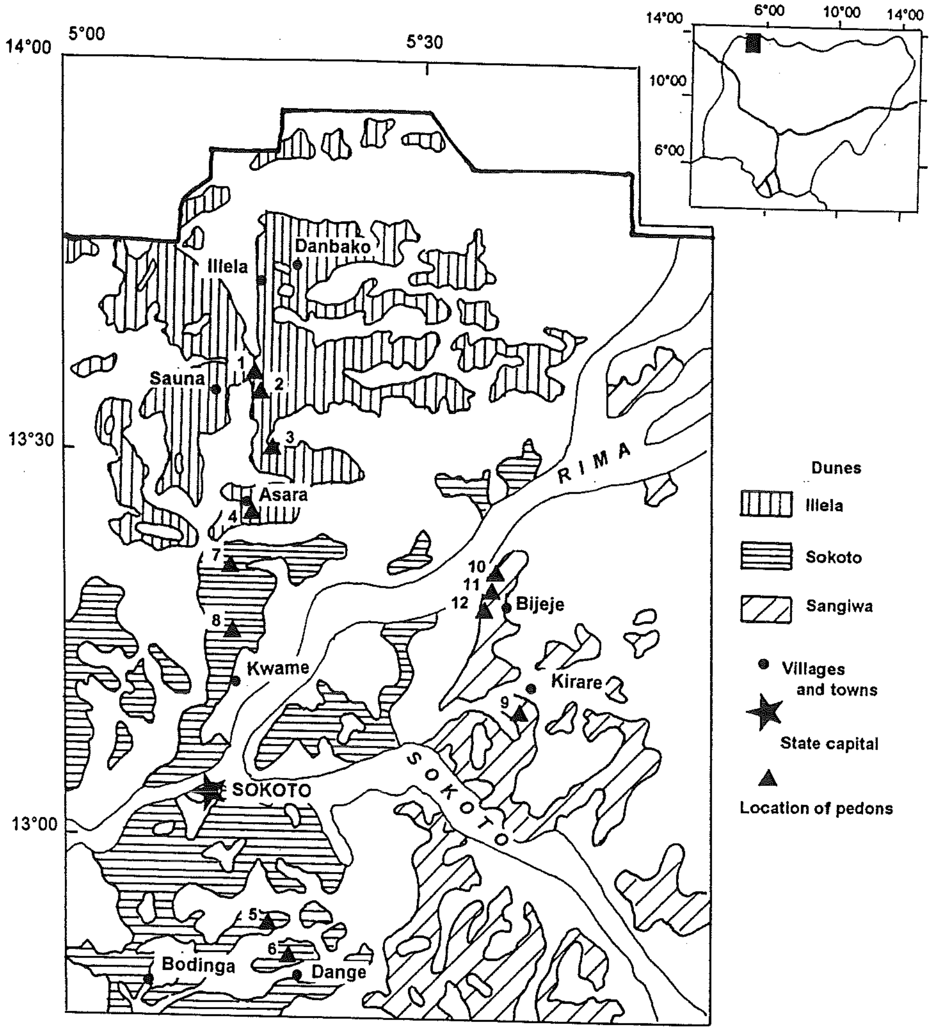


Fig.1. - Distribution of sand dune fields in part of northwestern Nigeria and location of the pedons.

practices requires at the farmer's level. Groupings of these soils based on a combination of the overall measured properties, as being currently done in numerical taxonomy, would aid in making rational decisions concerning the fertility affinity between them.

This paper therefore, describes the results of numerical ordination and classifications of a set of surface soils for their fertility affinities and compares them with the results of the conventional approach.

## MATERIALS AND METHODS

### Description of Study Area.

The study area lies between latitude 10°20' and 13°45' and longitude 3°50' and 6°50'E. The present day climate of the area is that of hot sudano-sahelian savanna bordering on semi-aridity towards the north. The total annual rainfall is about 600 mm while the annual air temperature ranges from 13°C to 38°C with a mean of 26°C (KOWAL & KNABE, 1972). Three sand dunes; Sokoto, Sangiwa and Illela dunes have been identified (FAO, 1969) and each of them is subdivided into a deep and a shallow phase (Fig. 1).

Tab.I. - Details of Sampling Sites

| S/No of sites | Dune type | Subgroup | Family* |
|---|---|---|---|
| 1 | Illela deep | Ustic Quartzipsamments | - |
| 2 | " " | Arenic Haplustults | Coarse Loamy |
| 3 | Illela shallow | Ustic Quartzipsamments | - |
| 4 | " " | " " | - |
| 5 | Sokoto deep | Typic Haplustults | Fine Loamy |
| 6 | " " | " " | Fine Loamy |
| 7 | Sokoto shallow | Lithic Haplustults | Coarse Loamy |
| 8 | " " | Ustic Quartzipsamments | - |
| 9 | Sangiwa deep | " " | - |
| 10 | " " | " " | - |
| 11 | Sangiwa shallow | " " | - |
| 12 | " " | " " | - |

*All soils are Isohyperthermic while Haplustults are of mixed mineralogy

The shallow phase refers to those dunes which are less than 2m to either the underlying geology or to an indurated layer while the deep phase are those thicker than 2m. Table I shows the characteristics of the soils used in this study. The sand dunes are predominantly quartz in composition and are extensively cultivated to millet (*Pennisetum typhoideum* Rich), guinea corn (*Sorghum bicolor* (L) Moenoh) and cowpea (*Vigna unguiculata* (L) Walp).

## Field and Laboratory Studies

Twenty-one soil properties for each of twelve soil sites were chosen for the numerical methods. At each site, five surface soils (0-20cm) were sampled within a quadrant of a hectare. Morphological properties were determined following the procedures outlined in the soil survey manual (Soil Survey Staff, 1981). Physico-chemical properties were also determined following standard laboratory procedures (BLACK, 1965). Soil pH was determined in 1/2.5 soil/water ratio while exchangeable cations and cation exchange capacity (CEC) were determined by leaching with IM $NH_4OAC$ (pH 7.0) solution. Available P was by the Bray 1 method (KURTZ AND BRAY, 1945) while available DTPA micronutrients, Cu, Zn and Mn were by LINDSAY AND NORVELL (1978).

## Numerical Taxonomy Methods

The means and standard deviations of the 21 properties for the sixty surface soils are given in Table II. Coding of the morphological properties follows methods of CAMPBELL *et al* (1970) but modified slightly (Appendix). Values for each character used were standardized, using the zero mean and unit variance method (SNEATH & SOKAL, 1973) in order to remove distortion in values. The standardized values were then used to calculate similarity coefficient in a 12 x 21 (soil sites x character) matrix.

Two kinds of procedures were used to express similarity relationships among the soils: principal component analysis and similarity coefficient analysis. All computations were carried out on an Olivetti 386 computer using Statgraphic 2.1 program. For the similarity coefficient analysis, the Euclidean measure of distance which has been reported to be of practical values in soil studies (CIPRA *et al* 1970; CUANALO & WEBSTER, 1970; SNEATH & SOKAL, 1973; ARKLEY, 1976) was employed in this present study. When all the similarity coefficients had been calculated, the soils were grouped hierarchically using SOKAL & SNEATH'S (1971) unweighted pair-group method (UPGM) strategy modified by imposing a critical value of dissimilarity for any group being formed. The critical values imposed was 0.150 UPGM has been reported by Rohlf (SOKAL & SNEATH, 1971) to give the best dendrograms.

Tab.II. - Mean and standard deviation of soil properties used in each of the three classifications

| No. | Properties | Mean | Std. deviat. | Classification All | Classification Fertility | Classification Morph. |
|---|---|---|---|---|---|---|
| 1 | Soil reaction (pH) | 5.70 | 0.93 | x | x | |
| 2 | Organic carbon | 1.12 | 0.36 | x | x | |
| 3 | Available Phosphorus. | 13.86 | 12.17 | x | x | |
| 4 | CEC | 1.81 | 0.62 | x | x | |
| 5 | Exchange acidity | 0.46 | 0.24 | x | x | |
| 6 | Exchangeable Ca | 0.82 | 0.30 | x | x | |
| 7 | Exchangeable K | 0.08 | 0.04 | x | x | |
| 8 | Exchangeable Mg | 0.29 | 0.11 | x | x | |
| 9 | Silt | 3.83 | 2.86 | x | x | |
| 10 | Clay | 4.83 | 1.99 | x | x | |
| 11 | Sand | 91.50 | 2.94 | x | x | |
| 12 | DPTA Cu | 0.75 | 0.29 | x | x | |
| 13 | DPTA Zn | 1.70 | 0.34 | x | x | |
| 14 | DPTA Mn | 11.52 | 6.43 | x | x | |
| 15 | Iron oxide | 0.396 | 0.27 | x | x | |
| 16 | Hue | | | x | | x |
| 17 | Value | | | x | | x |
| 18 | Chroma | | | x | | x |
| 19 | Texture | | | x | | x |
| 20 | Structure | | | x | | x |
| 21 | Consistence | | | x | | x |

Three numerical ordination and classification were carried out, each using a different suite of properties. The three were (i) using all soil properties for which data was available, (ii) using only morphological properties (field observations) and (iii) using only physico-chemical properties relevant to soil fertility. Table II shows the properties used in the classification listed above. Specific details not discuss here are available in SNEATH AND SOKAL (1973).

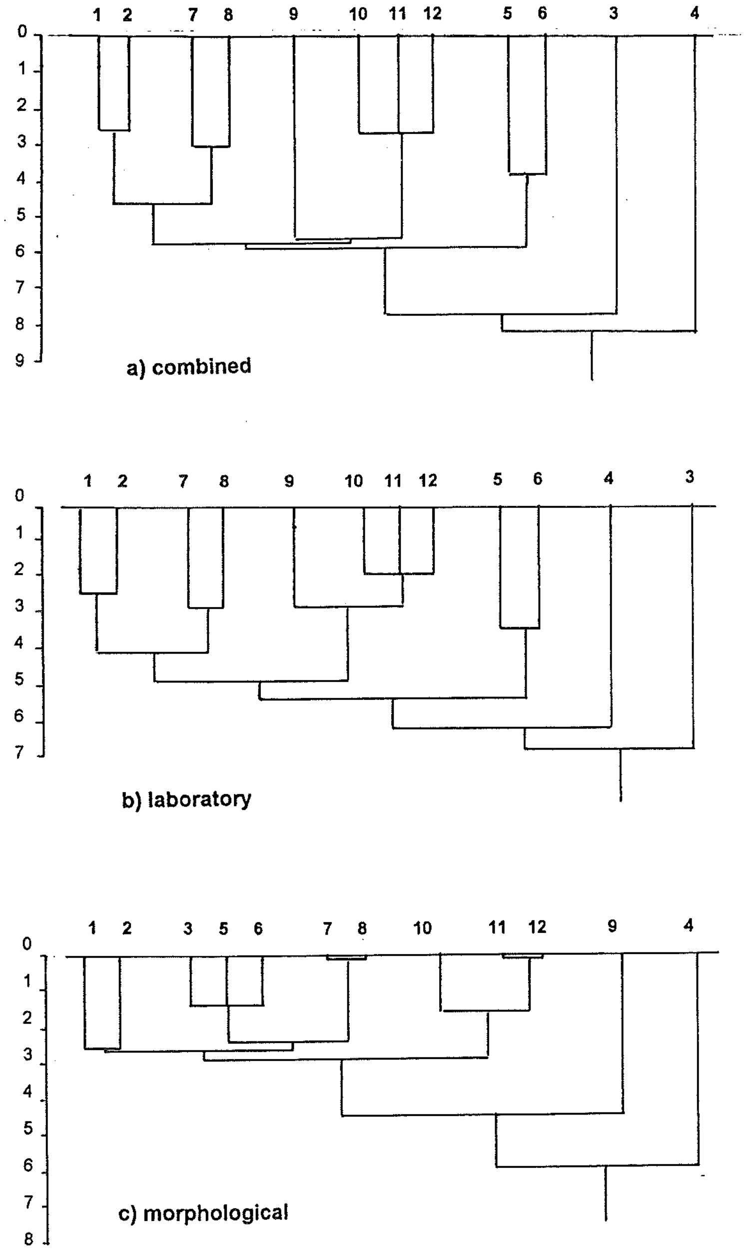


Fig.2. - Dendrogram of fertility affinities derived from Euclidian distance matrix.

a. Based on all measured field and laboratory data

b. Based on laboratory data only

c. Based on morphological data only

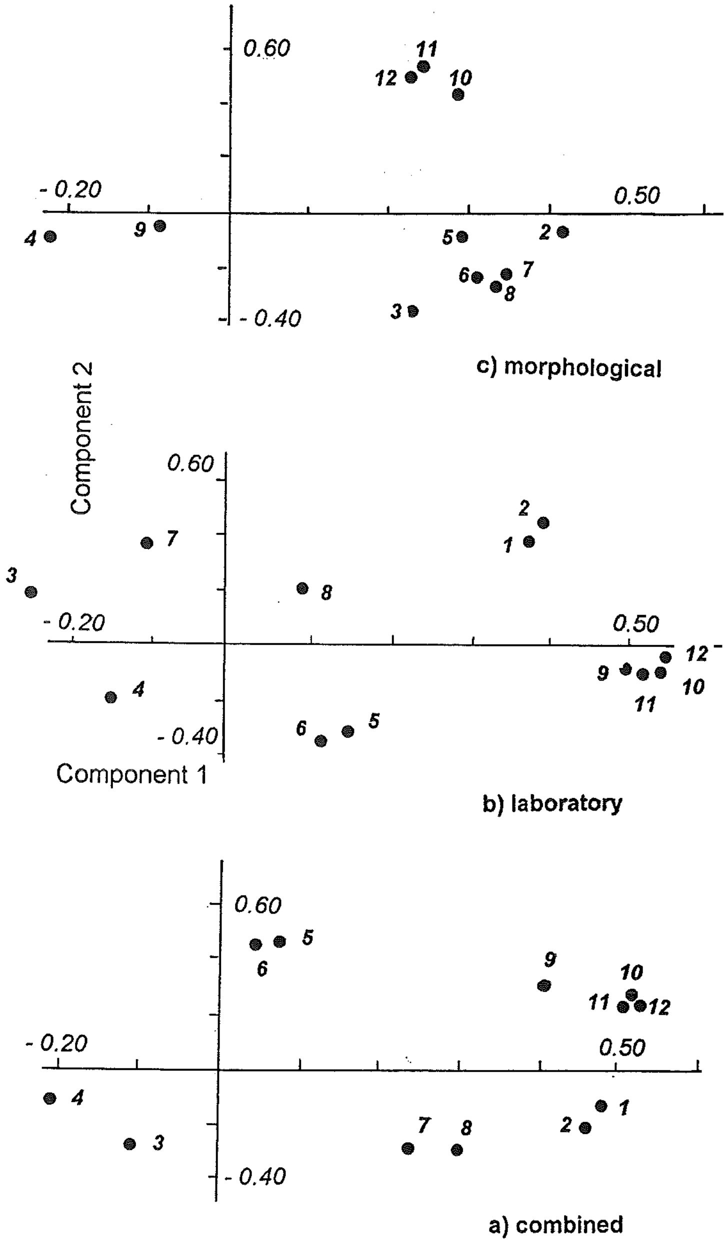


Fig.3. - Two dimensional representation of the fertility affinities showing the first and second component axes. a. Based on all measured field and laboratory data
b. Based on laboratory data only
c. Based on morphological data only

## RESULTS AND DISCUSSION

The dendrograms resulting from the different suites of properties but based on the Euclidean measure of distances are shown in Fig. 2. The resulting graphs from the principal component analyses are also shown in Fig. 3. The proportions of the total variation taken up by the first 6 principal components in the various analyses are listed in Table III.

Tab.III. - Contribution to principal components and percentage of variance

| Component N° | Properties | Percentage of Variance | Cumulative Percentage |
|---|---|---|---|
| | A. For all properties mesured | | |
| 1 | (Avail. P, Exch. Ca & Mg) | 30.70 | 30.70 |
| 2 | (OC, CEC, Clay, DPTA Mn) | 21.21 | 51.91 |
| 3 | (Texture, Consistence) | 17.93 | 69.84 |
| 4 | | 11.03 | 80.87 |
| 5 | | 7.50 | 88.37 |
| 6 | | 4.81 | 93.18 |
| | B. For fertility trlated properties only | | |
| 1 | (Avail. P, CEC, Exch. Ca & K) | 35.03 | 35.03 |
| 2 | (OC, Exch. Mg, DPTA Mn) | 23.54 | 58.57 |
| 3 | $Fe_2O_3$, Acidity, Clay) | 16.89 | 75.47 |
| 4 | | 12.06 | 87.54 |
| 5 | | 5.98 | 93.52 |
| 6 | | 3.84 | 97.35 |
| | C. For field/morphological properties only | | |
| 1 | (Colour value, structure, consistence) | 42.95 | 42.95 |
| 2 | (Chroma) | 22.94 | 65.90 |
| 3 | (Hue) | 15.24 | 81.14 |
| 4 | (Texture) | 12.69 | 93.83 |
| 5 | | 3.23 | 97.06 |

Comparison of the dendrograms and the ordination analysis (Fig. 2 and 3) with our classification based on USDA Soil Taxonomy (Tab.I), shows that there is broad agreement between them. This is especially so when all available data (both field and laboratory) were used and at a higher level of classification. This similarity may be attributed to the fact that the exchangeable Ca and Mg and available P, which made the biggest contribution to the first principal component, are related to the nutrient element status or base saturation. Organic matter (OC), cation exchange capacity (CEC), clay and available Mn, which also contributed largely to the second principal component, are mostly closely related to the exchange capacity of the soil. Exchange capacity and the base saturation are also two criteria most commonly used in USDA Soil Taxonomy (Soil Survey Staff, 1975) hence, the close similarity between them. However, at the lowest level of classification the similarity breaks down. While classification based on Soil Taxonomy (Tab.I) shows only two clusters, Haplustults and Quartzipsamments, the numerical classifications (Fig. 2 and 3), on the other hand, show four clusters with two unattached sites. These differences might be ascribed to the fact that *Soil Taxonomy* (Soil Survey Staff, 1975) places soils into groups which are homogeneous in terms of selected porperties (diagnostic horizons), some of which might be totally unrelated to soil fertility. Numerical taxonomy, on the other hand, group soils using all measured properties in unweighted forms. Secondly, most of the soil properties have values which are lower than the critical limits quoted in literature and are statistically at par between groups, hence their being grouped together.

From the numerical classifications (Fig. 2 and 3), four main groups and two unattached soil sites were delineated at the lowest level. All the soils of the Illela deep dunes are placed together in group I but those of its shallow phase are separated into groups V and VI. The soils of the Sokoto deep dunes are isolated as group II while those of the shallow phase are placed together in group III. The soils of both the shallow and the deep phases of the Sangiwa dunes are however, all placed together in group IV. Interestingly, soils of groups V and VI remained unattached in all our numerical classifications. The two groups were observed to contain soils which have phosphatic sediments at shallow depths, hence had high available phosphorus and few occurrence of carbonate rings, indicating calcification in these soils. The nature of the underlying geology and climate, therefore, seems to be the controlling factor in the separation of these two groups. Climate in the study area is however, controlled by the geographical location as aridity increases northwards. On the other hand, groups I to IV have soils occurring on dunes of similar meso-relief and are located geographically together (Fig. 4)

It is clear that within the groups, there are similar soils with strong fertility affinities and consistent differences between the groups (Tab.IV). The mean values of some of the soil properties for the six groups are shown in Table IV. There are significant differences ($P = 0.05$) in most of the soil properties studied, even though most of the values are below the critical limits, except in the levels of available copper, manganese and zinc. The micronutrient levels are also above the critical limits quoted in literature (LINSDAY AND NORVELL, 1978). For soils that are inherently poor in nutrients, the high contents of the micronutrients and the similar levels in the three dune soils point to a possible occurrence, in the parent materials of the dunes, of minerals rich in these elements. Significant differences ($P = 0.05$) exist in soil reaction, organic carbon, available P, CEC, acidity, exchangeable Ca, Clay and Free iron oxide.

Tab.IV. - Comparison of soil properties of 6 classes derived the sand dune soils classes

| Class (n) | pH | OC mg kg$^{-1}$ | avail. P mg kg$^{-1}$ | CEC cmol$_c$ Kg$^{-1}$ | Exchangeable bases cmol$_c$ Kg$^{-1}$ | | | Silt g kg$^{-1}$ | Clay g kg$^{-1}$ | DPTA mg kg$^{-1}$ | | | Free fe oxide g kg$^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Ca | K | Mg | | | Cu | Zn | Mn | |
| I (8) | $4.9^{a}$ | $0.8^{a}$ | $15.4^{bc}$ | $1.0^{a}$ | $0.5^{a}$ | $0.04^{a}$ | $0.18^{a}$ | $15^{a}$ | $30^{a}$ | $0.63^{a}$ | $1.76^{a}$ | $4.0^{a}$ | $2.75^{ab}$ |
| II (8) | $5.3^{ab}$ | $1.3^{ab}$ | $8.7^{ab}$ | $2.6^{d}$ | $0.8^{ab}$ | $0.06^{a}$ | $0.27^{a}$ | $30^{a}$ | $80^{b}$ | $1.19^{a}$ | $1.35^{a}$ | $20.4^{c}$ | $6.12^{bc}$ |
| III (8) | $6.5^{bc}$ | $0.9^{a}$ | $15.4^{bc}$ | $1.8^{bc}$ | $0.9^{abc}$ | $0.05^{a}$ | $0.39^{ab}$ | $20^{a}$ | $40^{a}$ | $0.68^{a}$ | $2.05^{a}$ | $13.2^{bc}$ | $4.70^{ab}$ |
| IV (16) | $5.4^{ab}$ | $1.1^{a}$ | $4.2^{a}$ | $1.5^{ab}$ | $0.7^{a}$ | $0.12^{b}$ | $0.22^{a}$ | $75^{b}$ | $40^{a}$ | $0.68^{a}$ | $1.53^{a}$ | $12.2^{b}$ | $1.83^{ab}$ |
| V (4) | $5.5^{ab}$ | $1.0^{a}$ | $46.36^{d}$ | $2.5^{cd}$ | $1.4^{c}$ | $0.07^{a}$ | $0.39^{ab}$ | $10^{a}$ | $70^{ab}$ | $0.54^{a}$ | $2.30^{a}$ | $10.4^{ab}$ | $10.75^{c}$ |
| VI (4) | $8.0^{bc}$ | $2.0^{b}$ | $24.1^{c}$ | $2.5^{cd}$ | $1.3^{bc}$ | $0.13^{b}$ | $0.50^{b}$ | $20^{a}$ | $50^{ab}$ | $0.79^{a}$ | $1.70^{a}$ | $12.8^{abc}$ | $3.20^{ab}$ |

*Means followed by the same letter in a column are not significantly different (LSD, $\alpha = 0.05$)

TAB.V. - Correlation between soil morphological properties and laboratory data

| | pH | Avail. P | Exch. Ca | Exch. Mg | Exch. K | OC | CEC | Clay | Avail.Mn | Avail. Zn | Fe-oxide |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hue | | | | | 0.58* | | | | | | |
| Value (dry) | - 0.58* | - 0.84*** | - 0.82** | - 0.76** | | | | | | - 0.61* | - 0.59* |
| Value (moist.) | | - 0.61* | | | | | | | | | |
| Chroma (dry) | | | | 0.62* | | | | | | 0.68* | |
| Chroma (moist.) | | | | | | | | | | | |
| Texture | | | | | | | 0.74** | 0.86*** | | | 0.78** |
| Structure | | | | - 0.58* | | | | | | | |
| Consistence | - 0.78** | | | - 0.61 * | | - 0.78** | | | | | |

Significant at * P = 0.05 ** P = 0.01 ***P = 0.001 levels

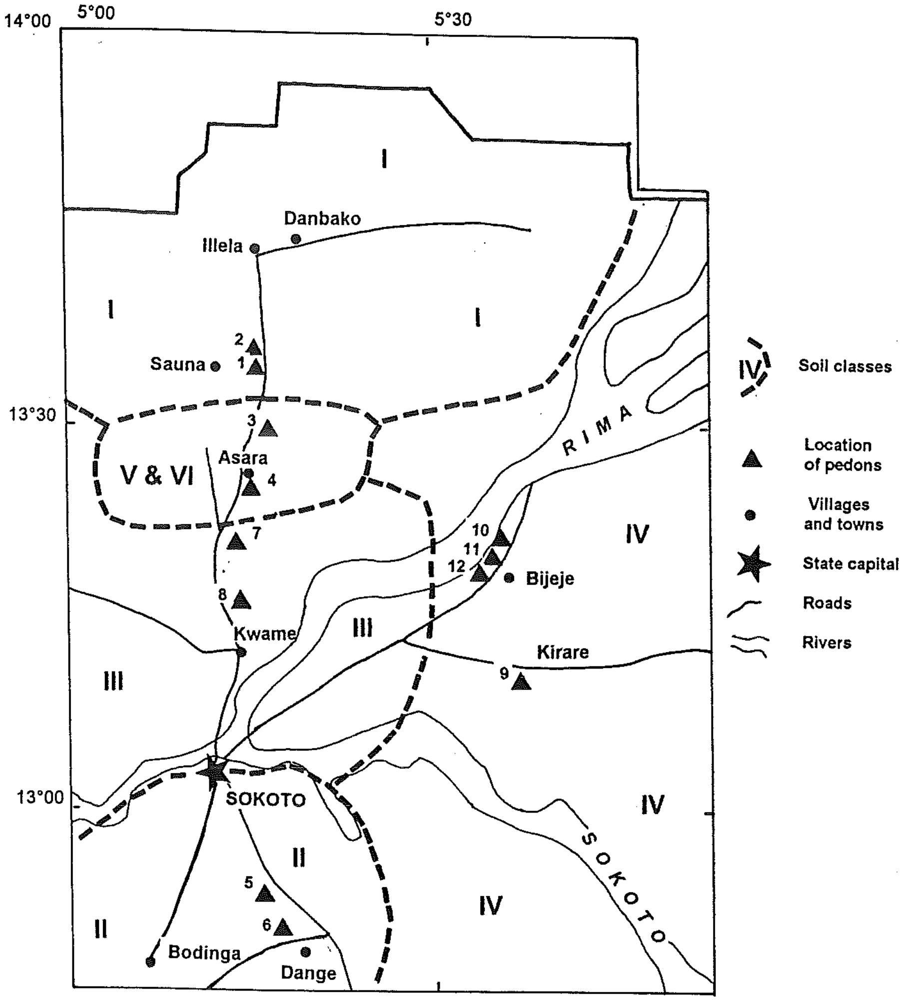


Fig.4. - Geographical distribution of soil classes based on numerical classifications.

These are the same properties identified for the 1st and 2nd principal components of our numerical classification. It is therefore, obvious, why our numerical classifications appear better than our classification based on Soil Taxonomy, in that the numerical classifi-cations were based on a combination of properties that show the most significant differences between the soils. In most cases, soils of groups V and IV were statistically at par for most of the soil properties studied and for few soil properties like CEC, organic carbon, clay and exchangeable Ca. Soils of groups V and VI were also at par, statistically, with soils of group II. The three groups, II, V and VI, therefore, seem to be more closely linked or related than the other groups. This is obvious from their positions on the dendrograms (Fig.2). Generally, the fertility levels in the soil groups are in the order VI = V > III > II > IV > I. This corresponds to Illela shallow dunes where the influence of the underlying geology is greater through admixture with the dune materials to Sokoto shallow dunes with similar effect of underlying geology. Next is Sokoto deep dunes followed by the Sangiwa dunes and the deep phase of Illela dunes which is predominantly quartz in composition (RAJI *et al.* 1996). This trend indicates that in this sand dune soils which are predominantly quartz in composition, the underlying geology has a greater influence on the fertility of the soils. The results of the numerical classifications also indicate a probable need to re-examine the current USDA *Soil Taxonomy* classification for soils in groups V and IV, which are classified as Quartzipsamments and soils of sites 2 and 7 in groups I and III which are also classified as Kanhaphustults (RAJI *et al.* 1996). From the results of the numerical taxonomy, it is clear that soils in groups V and VI have significantly higher values of available P, exchangeable Ca and soil reaction. These properties are of course very important to the overall soil fertility. Soils in sites 2 and 7 also consistently grouped along other Quartzipsamments in groups I and III. This is even the case in the numerical classification based on only morphological properties, which although showed close similarity to other numerical classifications based on laboratory and all available data, but is slightly different at the lowest level of classification (Fig. 2 and 3). The close similarity might be attributed to the fact that the first principal component, for classification based on morphological properties only, which is made up of consistence, structure and colour value account for over 40 percent of the total variance, close to those accounted for by the first two principal components of the other suites of properties (Tab. III). The close similarity may also be attributed to the fact that most of the soil morphological properties correlated significantly (Tab. V) with some laboratory data.

The correlation between soil morphological properties and some laboratory data (Tab. V) is of interest. Consistence would appear to have predictive value for organic matter ($r = -0.78$, $P = 0.01$), soil reaction ($r = -0.78$, $P = 0.01$) and exchangeable magnesium ($r = -0.61$, P 0.05). The correlation between colour value of dry soil and many soil properties (Tab. V) points to the possibility of using it as an indication or index of soil fertility in these soils. The negative correlation between value (dry) and the soil properties is due to the ranking of value from 1 (black) to 8 (white) in the Munsell notation. Reversal of ranking as explained by RUSSELL & MOORE (1967) would result in positive correlations.

## CONCLUSION

The numerical classification and ordination of these closely related sand dune soils for fertility affinity, seems to be better than the results of systematic Soil Taxonomy for the same soils. There is also close resemblance between the different methods of numerical classification and for the different suite of properties. There seems, therefore, to be fairly good relationship between field (morphological) and laboratory parameters for classifications based on the former to have considerable predictive value for certain laboratory measurements. Results of this study also indicate a possibility of using colour value of dry soil as an index of soil fertility in the dune soils. Meso-relief, thickness, geographical location, and the underlying geology are the main factors influencing the fertility affinities between the soils studied. There is need for further work in the use of numerical taxonomy to soil fertility studies, since quantification of the overall properties will give a better fertility affinity status of soils which would have otherwise been grouped together.

## REFERENCES


ARKLEY, R.J., 1976. Statistical methods in soil classification research. *Advances in Agronomy*, 28, 37-70

BLACK, C.A., 1965. *Methods of Soil analysis.* Agron. No 9, Madison, Wisconsin, USA.

BUOL, S.W., SANCHEZ, P.A., CATE, R.B. & M.A., 1975. Soil Management in Tropical America. N.C. State University, Raleigh, N.C., USA, 126p.

CAMBELL, N.A., MULCAHY, M.J. & McARTHUR, W.M., 1970. Numerical classification of soil profiles on the basis of field morphological properties. *Australian J. of Soil Research*, 8, 4358.

CHANG, J.M. & CHEN, Z.S., 1985. *A study on the Fertility characteristics of Taiwan paddy soils by Numerical Taxonomy methods.* FFTC Book series, No 29.

CIPRA, J.S., BIDWELL, O.W. & ROHLF, F.J., 1970. Numerical Taxonomy of soils from nine orders by duster and centroid component analysis. *Soil Sc. Soc. Am. Proc.*, 34, 281-287.

CUANALO, H.E., DELAC & WEBSTER, R., 1970. A comparative study of numerical classification and ordination of soil profiles in a locality near oxford, I. Analysis of 85 sites. *J. Soil Sci.*, 21. 340 -352.

FAO, 1969. Soil and water Resources Survey of the Sokoto Valley, Nigeria: Final report. Vol. 5: Soil Survey and Land Classification. FAO/UNESCO, Rome, 204p.

GRIGAL, D.F. & ARNEMAM, H.F., 1969., Numerical classification of some forested Minnesota soils. *Soil Sci. Soc. Am. Proc.*, 33, 433-438.

KOWAL, J.M. & KNABE, D. T., 1972. *An agroclimatological atlas of the Northern States of Nigeria with explanatory notes.* ABU press, Zaria, 111 p.

KURTZ, L.T & BRAY, R.H., 1945. Determination of total, organic and available forms of phosphorus in soils. *Soil Sci.*, 59, 39-45.

LINDSAY, W.L. & NORVELL, W.A., 1978. Development of DTPA soil test for Zinc, Iron, Manganese and Copper. *Soil Sci. Soc. Am.J.*, 42, 321-428.

MATHAN, K.K., NAAROJAN, S. & MANENDRAN, P.P., 1994. Application of fertility capability classification concept in major soil groups of Kamarajar District. *J. Indian Soc. Soil Sci.*, 42, 416-420.

MOORE, A. W. & RUSSELL, J.S., 1967. Comparison of coefficients and grouping procedures in numerical analysis of soil trace element data. *Geoderma,* 1, 139-158.

MOORE, A.W., RUSSELL, J.S. & WAND, W.T., 1972. Numerical analysis of soils: A comparison of three soil profile models with field classification. *J. Soil Sci.*, 193-209.

RAJI, B.A.., ESU, I.E., CHUDE, V.O., OWONUBI, J.J. & KPARMWNG, T., 1996. Properties, classification and management implication of soils of Illela dunes, NW Nigeria. *J. Science of Food and Agric.*, 70, 425-432.

RAYNER, J. H., 1966. Classification of soils by numerical methods. *J. Soil Sci.*, 17, 79-92.

RUSSELL, J. S. & MOORE, A.W., 1967. Use of a numerical method in determining affinities between some deep sandy soils. *Geoderma,* 1, 47-68.

SANCHEZ. P.A., COUTO, W. & BUOL, S.W., 1982. The fertility capability soil classification system interpretation, applicability and modification. *Geoderma,* 27, 283-310.

SNEATH, P.H.A. & SOKAL, R.R., 1973. *Numerical Taxonomy: The principles and practice of numerical classification.* Freeman and Co., San Francisco, 573p.

Soil Survey Staff, 1975. *Soil Taxonomy: A basic system of soil classification for making and interpreting Soil Surveys.* USDA Agric. Handbook 436, U.S. Govt. Printing Office, Washington, D.C., 734 p.

Soil Survey Staff, 1981. Examination and description of soils in the field. In: *Soil Survey Manual.* USDA Agric. Handbook 18. US Govt. Printing Office, Washington, D.C.

Soil Survey Staff, 1994. *Keys of Soil Taxonomy.* SMSS Technical Monograph No 19: Virginia Polytechnic Inst. and State University, 422 p.

## APPENDIX

Numerical coding of properties based on observed morphological properties

| | | |
|---|---|---|
| 1. | Colour | (Munsell soil color chart) |
| | a. Hue | Decreasing redness from 7.5 YR (denoted by 1), 2.5 YR (denoted by 3) through to 5Y (denoted by 8) |
| | b. Value | Value used as recorded in the field |
| | c. Chroma | Used as recorded in the field |
| 2. | Texture | Increasing clay content from 5 % clay (denoted by 1), 10 % clay (denoted by 2) through to strong (denoted by 4) |
| 3. | Structure | Increasing strength from structureless/single grain (denoted by 1), weak (denoted by 2) through to strong (denoted by 4) |
| 4 | Consistence | Increasing consistence in the moist state from loose (denoted by 1), very friable (denoted by 2) through to extreme (denoted by 6) |

Modified from CAMBELL, N.A., MULCAHY, N.J. & McARTHUR, W.M., 1970.