Quantifying Soil Morphology in Tropical Environments: Methods and Application in Soil Classification
Anne Gobin,* Paul Campling, Jozef Deckers, and Jan Feyen

ABSTRACT

We tested the hypothesis that readily observed and easily measured morphological variables can be used to characterize the soils sampled and described in southeastern Nigeria for purposes of land use and management. Field tests were developed for estimating soil texture and amount of ironstone nodules. Two new soil color indices provided an immediate means of diagnosing the soil drainage regime in case of the color index (CI) and soil forming processes in tropical soils in case of the redness index (RI). The indices correlated negatively with organic C content \( (R = -0.39) \) and positively with dithionite-extracted \( Fe_2O_3 (0.44) \) and \( Al_2O_3 (0.51) \). Inexpensive field tests for color, texture, and ironstone can be quantified using color indices and laboratory measurements. The local soil classification was quantified by means of color indices (RI, CI) and percentages of ironstone, sand, silt, and clay measured in the A horizon. A classification based on soil texture, ironstone, and color was used to define classes for the B horizon. The two first principal components (PC) extracted from soil morphological variables measured on the upper three horizons of 72 pedons explained 64.7\% of the total variance. Nonhierarchical clustering performed on the two PCs produced seven clusters that compare well with the great groups of U.S. soil taxonomy. Principal component analysis on 20 soil chemical and morphological variables confirmed that soil texture, ironstone, and soil color account for most of the variation of the soils and provide an efficient means of characterizing tropical soils derived from sedimentary parent material.

The increasing use of geographical information systems and earth observation techniques in land resources analysis has highlighted the need for quantitative data on the spatial distribution pattern of soil characteristics. However, many soil surveys have concentrated on the vertical sequence of horizons within pedons, paying less attention to the spatial distribution (FAO, 1998). Parametric soil surveys concentrate on measuring single soil characteristics, and provide, in concert with process modeling, a suitable paradigm for spatial prediction across low-surveyed regions (McKenzie and Austin, 1993; Moore et al., 1993). The use of readily observed and quantifiable morphological characteristics to distinguish between different soils as a first step to determining their spatial extent is our major concern here.

Soil morphological descriptions are commonly recorded and mostly used to aid classification purposes (Soil Survey Staff, 1998; FAO, 1998). Standard soil morphological descriptions have been quantified and combined in a soil profile development index for evaluating soil development (Bilzi and Cilkoz, 1977; Meixner and Singer, 1981; Harden, 1982). In addition, McKenzie and Jacquier (1997) describe the use of soil morphological descriptions together with inexpensive field tests to derive soil hydraulic properties in low-surveyed regions. Last, soil color indices present a quantified approach for assigning drainage class to a soil (Megonigal et al., 1993; Thompson and Bell, 1996) and assessing the Fe oxide mineralogy (Torrent et al., 1980; Mokma, 1993).

Farmers often describe soils in combinations of single morphological characteristics (e.g. red sand or stone) and often relate their decision-making on land use and management to these soil descriptions (Gobin et al., 1998, 1999). Quantifying these morphological characteristics opens new perspectives for incorporating farmers' knowledge into land resources information systems, and enables statistical modeling to be used. Farmers' knowledge could benefit scientific understanding of soils, contribute to international agricultural development, and facilitate exchange between farmers and researchers (Sandor and Furbee, 1996; Alexander, 1996; Habarurema and Steiner, 1997; Norton et al., 1998).

The objectives of this study were to quantify field observations of soils made by scientists and local farmers, relate field observations to laboratory analysis, and identify soil variables for distinguishing soils in a tropical area. Our method for quantifying field observations uses laboratory techniques and color indices measured on 72 pedons. We developed two soil color indices that incorporate a weighting factor for matrix and mottling colors, and we identified soil variables that distinguish the soils using exploratory methods, analysis of variance, and multivariate analysis.

MATERIALS AND METHODS

Study area

The 589-km\(^2\) study area comprises the River Ebonyi headwater catchment and a part of the Udi-Nsukka Plateau located


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Abbreviations: BS, base saturation; CEC, cation-exchange capacity; CI, color index; CV, coefficient of variation; EA, exchangeable acidity; PC, principal component; RI, redness index; RR, redness rating; SD, standard deviation.
in Enugu State, Nigeria (Fig. 1). The study area traverses from west to east a part of the Udi-Nsukka Plateau and Escarpment and a section of the Cross River Plains, characterized by a complex sedimentary history (Benkhelil, 1988). In general, argillaceous rocks underlie the Plains, whereas the Plateau and Escarpment are formed by sandstone. Flat-topped hills or ridges with surface ironstone are common on the Plateau and east of the Escarpment and represent remnants of the Coal Measure formations (Jungerius, 1964). The fluvial landscape farther on the Plains is characterized by a meandering river channel bordered by narrow river banks, with seasonally submerged backswamps from combined river flooding and upland run-on (Gobin et al., 1998). The upper interfluve is undulating to rolling, whereas the lower interfluve is flat to undulating.

The region has a humid tropical climate with a distinct dry season between November and March and an annual rainfall averaging ~1500 mm yr⁻¹ (Köppen climate classification is Aw). The area is situated in the transition zone between lowland, Guinea-Congolian, wetter-type rainforest and Guinea savanna, resulting in a mosaic vegetation pattern (Hopkins, 1979; White, 1992). Luxuriant evergreen forest fringes the valley bottom, whereas along seasonal streamlines corri-dors of semideciduous trees and bushes are found. Moist semideciduous forest occurs on the Plateau and shal-Copyright © 2000 Soil Science Society of America. All rights reserved.

ty dominating the Escarpment and denuded gravelly interfluve areas.

Field Methods

Soil profile observations were fully described according to the FAO guidelines (1990). Soil texture of the fine earth was approximated using a manual field test (International Land Development Consultants, 1981). The extent to which a tablespoon (~15 mL) of moist fine earth can be shaped is indicative of its texture (Table 1). On the Interfluve, the test was improved with the knowledge that loam is powdery when dry and leaves dirt on the skin when moist, and clay displays shining faces whenaugering. The occurrence of ironstone nodules, usually between 2 and 20 mm in size, was expressed in percentage surface covered: few (0-5%), common (5-15%), many (15-40%), abundant (40-80%), and dominant (>80%).

Soil colors were determined per horizon using the revised standard soil color charts (Takehara, 1992), which are based on the Munsell soil color chart (Munsell, 1954). The surface percentage of mottling and of each soil matrix color was estimated in the field. The mottling size was recorded in millimeters as fine (<5 mm), medium (5-15 mm), and coarse (>15 mm), and the mottling abundance was described as few (<2%), common (2-20%), and many (20-50%).

The term local soil classification refers to the classification that local farmers use to name the soils in the Igbo language. Techniques borrowed from participatory rural appraisal (Chambers, 1992) were conducted along the toposequence with the aid of two local village guides and trained interpreters and facilitators from outside the village to elicit the local soil classification scheme. Open-ended and semistructured interviews (Mettrick, 1993) were administered to villagers cultivating or owning fields within 50 m from a profile pit. The soil adjacent to each field was augered and described to verify its similarity with the reference soil pit and to facilitate the interview. Villagers were asked to compare their descriptions, knowledge, and name of a particular soil with soils located farther along the toposequence. Accounts of within-field variation were not incorporated into the classification scheme. Schematic diagrams were constructed for each of the toposequences, and the soil classification was verified during a group discussion involving farmers and village elders.

Laboratory Methods

Samples were taken per horizon, air-dried at an ambient temperature of ~25°C, crushed, and passed through a 2-mm sieve. The percentage of the fraction >2 mm was weighed, and the ironstones were weighed separately. Soil chemical analysis was carried out on the sieved fraction (Table 2). Soil classifications according to U.S. soil taxonomy (Soil Survey Staff, 1998) were inserted into the database. Local soil descrip-

### Table 1. Field test for soil texture

<table>
<thead>
<tr>
<th>Shape</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heap; soil remains loose and single grained</td>
<td>Sand</td>
</tr>
<tr>
<td>Ball of around 2.5 cm diameter</td>
<td>Loamy sand</td>
</tr>
<tr>
<td>Short, thick cylinder</td>
<td>Silt loam</td>
</tr>
<tr>
<td>Cylinder of 15 cm that breaks when bent</td>
<td>Loam</td>
</tr>
<tr>
<td>Cylinder of 15 cm can be bent in a U-form</td>
<td>Clay loam</td>
</tr>
<tr>
<td>Circle that shows cracks</td>
<td>Sandy clay</td>
</tr>
<tr>
<td>Circle without cracks</td>
<td>Clay</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shape</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>1424</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>719</td>
</tr>
<tr>
<td>Silt loam</td>
<td>1424</td>
</tr>
<tr>
<td>Loam</td>
<td>719</td>
</tr>
<tr>
<td>Clay loam</td>
<td>1424</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>719</td>
</tr>
<tr>
<td>Clay</td>
<td>1424</td>
</tr>
</tbody>
</table>

**Location of Pedons**

Generalized information on geology was derived from the 1:250 000 geological maps of Nigeria (Shell-BP, 1957). Vegetation, drainage, and relief were obtained from stereoscopic analysis of 1:40 000 aerial photographs from 1962 and topographic maps at a scale of 1:50 000. The study area was stratified according to combined geology, drainage, relief, and vegetation characteristics. Based on this stratification, 40 pedons were located along the steepest environmental gradients following the catena concept (Sommer and Schlichting, 1997) to sample the full range of soils in the study area. Soil pits were dug (Fig. 1) at representative locations of each landscape along the toposequences. These locations were identified using a clinometer, a compass, and a global positioning system (Trimble Pathfinder Basic and Software; Trimble, 1992). The catena concept was also employed in former soil surveys within the study area; 32 pedons were sited in the field and on the topographic map (Akamigbo and Opara, 1977; Federal Department of Agricultural Land Resources, 1985; Asadu, 1986; Nwadialor, 1989) (Fig. 1). A relational database (Prague and Irwin, 1997) was set up to process all information obtained on the 72 pedons.

**Fig. 1. Regional setting of the study area and location of pedons.**

**Techniques**

Schematic diagrams were constructed for each of the toposequences, and the soil classification was verified during a group discussion involving farmers and village elders.

**Laboratory Methods**

Samples were taken per horizon, air-dried at an ambient temperature of ~25°C, crushed, and passed through a 2-mm sieve. The percentage of the fraction >2 mm was weighed, and the ironstones were weighed separately. Soil chemical analysis was carried out on the sieved fraction (Table 2). Soil classifications according to U.S. soil taxonomy (Soil Survey Staff, 1998) were inserted into the database. Local soil descrip-
Table 2. Soil variables and analysis methods for soil samples.

<table>
<thead>
<tr>
<th>Soil variable†</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH(H2O) (pHw)</td>
<td>1:5 soil solution ratio of distilled water</td>
</tr>
<tr>
<td>pH(KCl) (pHK)</td>
<td>1:5 soil solution ratio of 1 M KCl</td>
</tr>
<tr>
<td>Organic C (OC)</td>
<td>Wet oxidation method (Walkley and Black, 1934)</td>
</tr>
<tr>
<td>Total N (N)</td>
<td>Kjeldahl</td>
</tr>
<tr>
<td>Available P (P)</td>
<td>Bray 1 (Bray and Kurtz, 1945)</td>
</tr>
<tr>
<td>Total Al and Fe (Al2O3, Fe2O3)</td>
<td>Dithionite extraction</td>
</tr>
<tr>
<td>Exchangeable acidity (EA)</td>
<td>1 M KCl extraction</td>
</tr>
<tr>
<td>Cation-exchange capacity (CEC)</td>
<td>Percolation with ammonium acetate at pH 7</td>
</tr>
<tr>
<td>Exchangeable cations (Ca, Mg, K, Na)</td>
<td>First percolate (atomic absorption spectrophotometer)</td>
</tr>
<tr>
<td>Particle-size distribution (sand, silt, clay)</td>
<td>Pipette method</td>
</tr>
<tr>
<td>Ironstone content (stone)</td>
<td>Weighing ironstone in fraction &gt;2 mm</td>
</tr>
<tr>
<td>Color indices (CI, RI, MoCI, MoRI)</td>
<td>Munsell color notation and Eq. [3] and [4]</td>
</tr>
</tbody>
</table>

† Abbreviations used for each soil variable are presented in brackets.

Soil Color Indices

Soil color based on the soil Munsell color chart consists of hue, value, and chroma. The color notations were converted into color indices to arrive at a single numerical value. Previously published work suggests that color indices are useful for quantifying differences in soil morphology. Hurst (1977) defined the Redness Rating (RR) as an assigned numerical value for hue, multiplied by chroma and divided by value. The RR proved a good discriminator between hematite and goethite and correlated highly with the fine earth hematite content in red Mediterranean soils (Torrent et al., 1980). Chroma, augmented with or without an arbitrary value for hue, and in both cases corrected for all mottle and matrix colors, corresponded well with the hydric conditions of seasonally saturated soils (Thompson and Bell, 1996). The decrease in Munsell value along a toposequence was found to be highly correlated with increased organic C content (Fernandez et al., 1988). A decreasing color number, which was based on value and chroma added to a numerical value for hue, was highly correlated with increasing organic C and to a lesser extent with Fe and Al content in Spodosols (Mokma, 1993). Harden (1982) and Harden et al. (1991) also developed Melanization, rubification, color lightening and color paling for desert soils.

Two new indices, a redness index (RI) and a color index (CI), combined and modified components from previous studies to suit soil colors typical for active tropical weathering and to incorporate a weighting for matrix and motting colors. Hues of all soil horizons in the study area ranged from 10YR (Yellowish Red) to 10R (Red) and were transformed to a numerical value for hue, multiplied by chroma and divided by value. A redness index (RI) and a color index (CI) were designed according to:

\[
RI = \frac{\sum_{i=1}^{n} P_i [HT_i, C_i]}{\sum_{i=1}^{m} S_i [HT_i, C_i]} + \sum_{i=1}^{m} S_i [HT_i, C_i]
\]

\[
CI = \frac{\sum_{i=1}^{n} P_i [HT_i, C_i]}{\sum_{i=1}^{m} S_i [HT_i, C_i]} + \sum_{i=1}^{m} S_i [HT_i, C_i]
\]

Where \( n \) is the number of matrix colors, \( V \) is the Munsell value, \( C \) is the Munsell chroma. The second terms of Eq. [2] and [3] are referred to as the motting redness index (MoRI) and motting color index (MoCI), respectively.

Statistical Analysis

The statistical analysis aimed at identifying soil variables that can be used to distinguish the different soils of the study area.

Exploratory and Correlation Analysis

Exploratory data analysis included descriptive statistics and a check for normality (SAS Institute, 1990) on all soil characteristics per horizon. Most soil variables were transformed to normal distribution using a natural logarithm or square root. Soil texture was transformed according to Eq. [5]; the amount of ironstone was transformed according to Eq. [6] (Webster and Oliver, 1990).

\[
sx = \arcsin \left( \frac{\sqrt{V}}{100} \right)
\]

\[
ly = \ln \left[ \frac{(y + 0.1)}{100 - (y + 0.1)} \right]
\]

Where \( x \) is sand, silt, or clay fraction expressed in percentage of fine earth, and \( y \) is percentage of ironstone. Correlation between the soil variables was examined.

Analysis of Variance

Mean, standard deviation (SD) and coefficient of variation (CV) were used to evaluate the within- and between-classes homogeneity in the different soil characteristics. Classes of the A horizon from all 72 pedons were based on the local classification, and classes of the B horizon were based on soil texture, ironstone, and color. A Fisher test was used to assess whether the class means are different from each other at the 0.05 significance level (SAS Institute, 1990). Multiple comparison was performed on each normalized soil variable, and subsequent statistical grouping was accomplished through Duncan-Waller multiple range tests at the 0.05 significance level (SAS Institute, 1990).
Multivariate Analysis

Multivariate analysis was used to identify interrelationships among soil chemical and morphological variables and to study differentiation patterns among the different soils using two matrices. A 72 by 27 matrix, X, consisted of nine normalized morphological variables per horizon for the upper three horizons (p) of 72 pedons (n), namely horizon thickness, sand, silt, clay, percentage of ironstone, and four soil color indices (RI, CI, MoRI, and MoCI). A second 72 by 60 matrix, Y, was created from 72 pedon observations on 20 normalized soil chemical, textural, and morphological variables for the upper three horizons. The calculations explained hereafter for X were also performed on Y. All normalized soil variables were standardized to zero mean and unit variance:

$$\tilde{X} = \sum_{i=1}^{n} \sum_{j=1}^{p} \left( x_{ij} - \bar{x}_j \right) s_j$$

[7]

Where \( x \) are the normalized observation values of the \( n \) by \( p \) matrix, \( \bar{x}_j \) is the mean vector of each normalized variable, and \( s_j \) the corresponding variance. The corresponding standardized correlation matrix (\( R_x \)) was defined:

$$R_x = \frac{\tilde{X}^T \tilde{X}}{(n - 1)}$$

[8]

\( R_x \) was examined according to three criteria (Jobson, 1992; SPSS, 1994):

Test for Zero Correlation. The correlation matrix equals the identity matrix when \( u \) has a \( x^2 \) distribution with 0.5\( p(p - 1) \) degrees of freedom, whereby \( u \) equals:

$$u = -\frac{\left( n - 6 - \frac{11}{2} \right) \sum_{j=1}^{p} \ln \lambda_j}{2}$$

[9]

Where \( \lambda_j \) are the eigenvalues of the correlation matrix. The test statistic is highly significant for matrices that are not orthogonal and thus appropriate for factoring.

Kaiser-Mayer-Olkin (KMO) Measure of Sampling Adequacy.

$$\text{KMO} = \frac{\sum_{i=1}^{p} \sum_{j=1}^{p} r_{ij}^2}{\sum_{i=1}^{p} \sum_{j=1}^{p} a_{ij}^2}$$

[10]

Where \( r_{ij} \) is the correlation coefficient and \( a_{ij} \) is the partial correlation coefficient between variables \( i \) and \( j \). Values for KMO below 0.5 are unacceptable.

Individual Measure of Sampling Adequacy (MSA,) for Each Variable. A value close to one is excellent, whereas values smaller than 0.5 require elimination of the particular variable.

$$\text{MSA}_i = \frac{\sum_{j=1}^{p} r_{ij}^2}{\sum_{j=1}^{p} a_{ij}^2}$$

[11]

Principal components (SAS Institute, 1990) were extracted from the correlation matrix, using the equation \( Z = XV \), where

Table 3. Values for redness index (RI) and color index (CI) from soils in the study area.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Munsell color</th>
<th>RI</th>
<th>CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxic horizon</td>
<td>10R4/8</td>
<td>25</td>
<td>2.45</td>
</tr>
<tr>
<td>Argilic horizon</td>
<td>7.5YR4/6</td>
<td>7.5</td>
<td>15</td>
</tr>
<tr>
<td>Iron mottling</td>
<td>2.5YR4/6</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Yellow mottling</td>
<td>10YR6/8</td>
<td>3.3</td>
<td>16.5</td>
</tr>
<tr>
<td>Redoximorphic</td>
<td>10YR6/2</td>
<td>0.8</td>
<td>10.5</td>
</tr>
</tbody>
</table>

† RI is calculated by Eq. [2], and CI by Eq. [3].
Table 4. Variation of properties within the A horizon, as categorized by the local soil.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Clay</th>
<th>Si+Cl</th>
<th>pH</th>
<th>OC</th>
<th>N</th>
<th>P</th>
<th>EA</th>
<th>CEC</th>
<th>BS</th>
<th>Identity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
<td>c</td>
<td>d</td>
<td>a</td>
<td>a</td>
<td>b</td>
<td>a</td>
<td>d</td>
<td>c</td>
<td>a</td>
<td>ab</td>
</tr>
</tbody>
</table>

1. Plateau, Rocky Sand, Red

Mean      0.8  79.8  3.9  16.3 20.2  15.9  11.9 3.8  6.3  0.7  1.2  15.4  4.8  4.2  22.8
SD        2.5  12.1  2.4  10.1 12.1  1.5  3.8  0.3  0.6  2.6  3.1  1.0  2.5  7.2
CV        323.7 15.1  61.6  62.3 59.9  9.4  32.3  5.6  48.3  43.0 107.6  61.7  59.8  31.6

2. Steep land, Sand, Red

Mean      0.1  89.1  3.3  7.6 10.9  13.8  8.0  5.1  0.5  41.4  12.3  0.6  3.7  28.4
SD        0.1  5.9  3.2  4.1  5.9  0.9  2.4  0.7  0.4  11.7  16.9  0.4  1.9  19.0
CV        137.5  6.6  98.8  54.1 53.9  6.4  30.5  13.2  81.1  28.2 137.6  59.4  51.2  66.9

3. Hill, Stone, Red

Mean      55.7  45.7  21.7  32.6 54.3  15.3  8.6  5.0  1.9  93.3  1.3  1.9  9.0  22.7
SD        21.3  14.6  7.5  13.8 14.5  2.7  3.0  0.6  0.6  22.7  2.1  1.5  3.7  21.1
CV        38.2  31.8  34.4  42.4 26.8  18.0  35.3  12.8 30.5  24.4 156.1  78.9  41.4  93.0

4. Small hill, Stony Clay, Red

Mean      18.6  46.4  26.1  27.6 53.7  11.7  4.1  5.1  1.6  81.4  1.5  2.2  6.5  37.2
SD        2.9  12.2  7.2  6.2 12.2  3.3  1.9  0.6  1.0  17.7  1.8  3.0  2.0  11.9
CV        15.3  26.3  27.7  22.4 22.7  28.4  46.9  12.5 58.9  21.8 123.4  139.8  31.4  32.1

5. Upland, Clay

Mean      2.7  49.7  35.0  15.4 50.3  10.8  2.9  5.3  0.9  60.7  2.7  0.6  5.1  30.8
SD        2.5  10.4  9.8  3.9 10.4  1.3  1.1  0.3  0.5  13.2  2.4  0.5  2.3  13.5
CV        92.3  21.0  28.1  25.7 20.7  12.1  38.2  6.3 54.0  21.8  89.5  78.1  44.6  43.9

6. Waterlogged Lowland, Heavy Clay

Mean      1.3  36.6  38.7  24.8 63.4  11.6  4.0  5.0  1.3  73.8  1.9  2.1  8.1  17.5
SD        2.4  15.0  10.2  9.4 15.0  2.0  1.7  0.3  0.2  15.4  1.4  1.0  3.0  9.0
CV        186.0  41.1  26.4  37.9 23.7  17.0  42.4  6.0 18.2  20.8 72.8  48.6  37.6  51.3

7. Riverside, Sand, and Rocky Sand

Mean      0.8  71.6  14.8  13.6 28.5  11.8  4.8  5.1  0.9  73.5  2.4  0.9  5.9  23.7
SD        1.4  23.9  13.5  10.5 23.9  4.3  3.1  0.2  0.7  62.3  2.0  0.7  6.0  16.4
CV        175.9  33.4  91.2  76.9 84.1  36.0  65.6  4.3 77.3  84.8  82.7  75.6  119.8  69.2

Group      c    b    c    c    e    d    c    c    a    e    b    a    a    ab

† Where mean is the arithmetic mean; SD is the standard deviation; CV is the coefficient of variation in percentage (= 100 × SD/mean); Group = Duncan-Waller grouping at the 0.05 significance level shown as letters in alphabetical order according to the magnitude of the mean; stone is expressed in weight percentage of sand; sand, silt, and clay are expressed in percentage of the fine earth fraction; Cl+Si is the silt plus clay fraction; Cl and RI are the color indices defined by Eq. [2] and Eq. [3]; pH is pH in H2O; OC is organic C; N is total N; P is available P; EA is exchangeable acidity; CEC is measured soil cation-exchange capacity; BS is base saturation.

Z is the matrix of unstandardized PCs, X the data matrix, V the matrix of eigenvectors with VV' = VV' = I, and I is the identity matrix (Jobson, 1992). The solution is an eigenvalue problem according to:

\[
\begin{pmatrix}
\sim X'X
\end{pmatrix}
\begin{pmatrix}
(n - 1)
\end{pmatrix}
- \Lambda = 0
\]

[12]

Where \( \Lambda \) is a diagonal matrix of eigenvalues of \( R_X \) (Eq. [8]), and \( V \) is orthogonal to \( R_X \). As the PCs are standardized, the values of the standardized components for \( n \) observations were determined using:

\[
\sim X = Z^*V^*
\]

[13]

Where \( Z^* = ZA^{-1/2} \) and \( V^* = A^{1/2}V \).

The \( p \) PCs are standardized linear combinations of the \( p \) original soil variables, with coefficients equal to the eigenvectors of the correlation matrix. The total variance \( (s_X) \) is given by:

\[
s_X = \sum_{i=1}^{p} \lambda_i
\]

[14]

Where \( \lambda_i \) is the eigenvalue or variance of the \( i \)th PC (PCi). Larger eigenvalues correspond with a larger explained portion of the total variance. All PCs were given a rank (eigenvalue number) according to their eigenvalue. The mean eigenvalue was used as a criterion to retain a reduced set of \( q \) components:

\[
\lambda_i \geq s^{-1} \sum_{i=1}^{q} \lambda_i
\]

[15]

The correlation between the original variables and PCs (loadings) are used for interpreting the PCs. Scatterplots of the observations in the plane of the PCs with the largest eigenvalues (scores) (Eq. [14]) provide a good estimate of the pattern of variation. The same procedure (Eq. [7]–[15]) was employed to extract PCs from matrix \( Y \).

Nonhierarchical cluster analysis following the k means algorithm was performed on the first two unstandardized PCs of matrix \( Z \) derived from matrix \( X \) (Eq. [12] and [13]). The Euclidean distance between group centroids was used to measure the proximity between groups:

\[
d^2 = \sum_{j=1}^{n} (\bar{x}_j - \bar{z}_j)^2
\]

[16]

Where \( d \) is the Euclidean distance between class \( r \) and \( s \), and \( \bar{x}_j \) and \( \bar{z}_j \) contain the coordinates of the centroids. The dispersion within classes, expressed as the sums of squares of deviations from the group means, was minimized through subsequent iterations in order to arrive at an optimal number of classes.
Records are reassigned until they are located in the group with the nearest centroid. The resulting clusters were compared with classification based on soil texture, ironstone, and soil color and with classification according to U.S. soil taxonomy.

**RESULTS**

**Field Observations**

In general, all pedons examined are closely related to parent material, which in turn is strongly associated with landform and landscape. On the Plateau, soils formed from sandstones and colluvial material derived from Upper Coal Measures occur on nearly flat slopes and dry valleys. They consist of reddish brown sandy loam over crumbly red sandy clay loam (2.5YR 4/8-10R 4/8). At Escarpment, soils are formed on sandstone and contain high amounts of sand throughout the profile; the subsoil contains weak crumb-structured sand with a very friable consistency. Soils rich in ironstone nodules dominate the Residual Hills. The Interfluve is characterized by soils derived from shale and having an argillic horizon. On the ridges and residual hills of the Interfluve, ironstone material occurs at the surface as lag gravel or at shallow depth, mostly in concretionary form. Fairly well-drained soils of the Upper Interfluve display

<table>
<thead>
<tr>
<th>Stone</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>OC</th>
<th>P</th>
<th>EA</th>
<th>CEC</th>
<th>BS</th>
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<td>29.0</td>
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<td>10.7</td>
<td>17.3</td>
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<td>2.7</td>
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<td>d</td>
<td>a</td>
<td>cde</td>
<td>ab</td>
<td>a</td>
<td>b</td>
<td>d</td>
<td>d</td>
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**RESULTS**

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<th>OC</th>
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<th>EA</th>
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<td>de</td>
<td>b</td>
<td>ab</td>
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<td>b</td>
<td>d</td>
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</table>

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<table>
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<th>Silt</th>
<th>Clay</th>
<th>OC</th>
<th>P</th>
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**RESULTS**

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<th>Clay</th>
<th>OC</th>
<th>P</th>
<th>EA</th>
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<td>c</td>
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**RESULTS**

<table>
<thead>
<tr>
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<th>OC</th>
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<tr>
<td>CV</td>
<td>77.4</td>
<td>44.9</td>
<td>30.0</td>
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<td>10.9</td>
<td>49.8</td>
<td>5.5</td>
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<td>d</td>
<td>bc</td>
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<td>ac</td>
<td>ab</td>
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</table>

**RESULTS**

<table>
<thead>
<tr>
<th>Stone</th>
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<th>Silt</th>
<th>Clay</th>
<th>OC</th>
<th>P</th>
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<td>78.1</td>
<td>54.9</td>
<td>19.2</td>
<td>46.8</td>
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<td>60.0</td>
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<td>CV</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>Group</td>
<td>d</td>
<td>b</td>
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<td>c</td>
<td>c</td>
<td>abc</td>
<td>cd</td>
<td>c</td>
</tr>
</tbody>
</table>

† Classes 5A and 5B correspond with Class 5 in Table 4, and classes 6A and 6B with Class 6. Where mean is the arithmetic mean; SD is the standard deviation; CV is the coefficient of variation in percentage (=100 × SD/mean); Group = Duncan-Waller grouping at the 0.05 significance level shown as letters in alphabetical order according to the magnitude of the class mean; stone is expressed in weight percentage of soil sand, silt and clay and is expressed in percentage of the fine earth fraction; CI+Si is the silt plus clay fraction; CI and RI are the color indices defined by Eq. [2] and Eq. [3]; pH is pH in H₂O; OC is organic C; N is total N; P is available P; EA is exchangeable acidity, CEC is measured soil cation-exchange capacity; BS is base saturation.
argillic subsurface horizons without pronounced mottling. Soils displaying red Fe mottles (2.5YR 4/6) within the 2-m profile depth occur on the slopes and River Terraces of the Upper Interfluve and on the somewhat better-drained areas of the Lower Interfluve. Seasonally waterlogged soils of the Lower Interfluve contain plinthite and a yellow mottling (10YR 6/8) in a gray soil matrix. Sandy to very sandy soils have developed on the riverbanks, whereas the soils of the backswamp have a finer texture and display redoximorphic features.

Farmers of the Nsukka Agricultural Zone can identify major soil types according to morphological characteristics of the soil to the depth they till or position in the landscape (Gobin et al., 1998, 1999). Although the local soil descriptions are not the same for every village, the underlying concepts or characteristics are similar. The characteristics used are easy to recognize and include the occurrence of ironstone, texture, and color, to which secondary soil properties such as workability, drainage, and water-holding capacity are attributed. The local soil names are based on the soil morphological characteristics, and a translation of the local names was used to reconstruct the local classification (Fig. 2). The soil names are directly linked to decision-making in land use and management. For example, soils of the residual hills and ridges that are named stone are considered marginal for agricultural uses.

Quantifying Field Observations

The huge differences in soils enabled the field estimation method to be tested for a wide range of soil textures. Compared with the laboratory textural analysis, the accuracy was 100% in detecting USDA soil textural classes. Field estimates of ironstone content corresponded with the following classes by weight percentage: few (<10%), common (10–30%), many (30–50%), abundant (50–70%), and dominant (>70%). RI and CI correlated positively with dithionite-extracted Fe$_2$O$_3$ ($R = 0.44$) and Al$_2$O$_3$ (0.51) and negatively with organic C content (−0.39) (Fig. 3). However, soil color is also dependent on the mineralogical composition of parent materials. Values for RI and CI were calculated for dominant mottle and matrix colors (Table 3). The highest values for RI were found in red soils dominated by sesquioxides (oxic), whereas low values for RI were found on gray and yellow soils (argillic). High values for CI corresponded with well-drained soils; intermediate values occurred on fairly well drained clayey soils (argillic); and the lowest values were associated with seasonally saturated soils (redoximorphic). Both indices were strongly correlated, but the difference in physical meaning, that is, relation to drainage (CI) and mineralogy (RI), justified keeping them both in as independent measurements.

Summary statistics for each soil variable showed that laboratory determination of texture, ironstone content, and the two color indices were useful in distinguishing the local soil classes (Fig. 2, Table 4). Despite its frequent use in soil science (Webster and Oliver, 1990), the CV is difficult to interpret, particularly in the case of proportional data. The classes “sticky sand/red” (1 [Class number: Table 4]), clay (5) and “heavy clay” (6) had the same SD for ironstone content, which made their CV, ranging from 92.3 to 323.7, entirely dependent on the mean (Table 4). However, the Duncan-Waller grouping provided an easy way of recognizing differences between soil classes for a particular soil variable; classes with the same letter for a group were statistically not significant from each other for that variable. “Stone” and “stony” related to the presence of ironstone nodules (>2-mm fraction). The ironstone of the “stone” (3) and “stony clay” (4) class content differed significantly from each other and from the other classes. The fine earth sand fraction (50 μm–2 mm) significantly separated the “sand” classes (1, 2, and 7) from the other classes. The local term “stickiness” of a soil, often translated as clay,

Table 6. Relation between landform and soil.

<table>
<thead>
<tr>
<th>Landform</th>
<th>Subgroup† (U.S. soil taxonomy)</th>
<th>Local class† (Local classification)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plateau</td>
<td>Typic or Rhodic Kandistox</td>
<td>Plateau, Sticky Sand, Red</td>
</tr>
<tr>
<td>Escarpment</td>
<td>Ustotic Quartzipsamments</td>
<td>Steepland, Sand, Red</td>
</tr>
<tr>
<td>Residual Hills</td>
<td>Ustic Kandihumults</td>
<td>Hill, Stone, Red</td>
</tr>
<tr>
<td>Upper Interfluve</td>
<td>Ustic Kandihumults</td>
<td>Upland, Stony Clay, Red</td>
</tr>
<tr>
<td>Lower Interfluve</td>
<td>Typic Plinthustults</td>
<td>Lowland, Clay, Dark</td>
</tr>
<tr>
<td>Floodplain</td>
<td>Aeric Endoaquents</td>
<td>Lowland, Heavy Clay, Gray</td>
</tr>
<tr>
<td>Riverbank</td>
<td>Oxyaquic Quartzipsamments</td>
<td>Riverside, Heavy Clay, Dark</td>
</tr>
</tbody>
</table>

† Only the dominant soils are presented.

Table 7. Loading values (between parentheses) of soil variables for principal component (PC) analysis performed on submatrix X containing only soil morphological variables.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Eigenvalue</th>
<th>% of variance</th>
<th>Positive loadings† (criterion: &gt;0.50 or first 6)</th>
<th>Negative loadings† (criterion: C &lt; −0.20 or last 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>10.93</td>
<td>45.6</td>
<td>Silt1 (0.93), Silt2 (0.93), Silt3 (0.91), MoCl13 (0.72), Stone1 (0.69), MoRI3 (0.68)</td>
<td>Sand1 (0.90), Sand2 (0.69), Sand3 (0.88), R1 (0.74), R2 (0.59), R3 (0.65)</td>
</tr>
<tr>
<td>PC2</td>
<td>4.59</td>
<td>19.1</td>
<td>C12 (0.70), C13 (0.70), R12 (0.66), R13 (0.59), C1 (0.58), Stone1 (0.58), Stone2 (0.58)</td>
<td>Sand1 (0.25), Sand2 (0.27), Sand3 (0.29)</td>
</tr>
<tr>
<td>PC3</td>
<td>2.53</td>
<td>10.5</td>
<td>MoRI2 (0.76), MoCl12 (0.73), MoRI3 (0.65), MoC13 (0.60)</td>
<td>Thick1 (0.30), Clay2 (0.26), Clay3 (0.23), Clay1 (0.29)</td>
</tr>
<tr>
<td>PC4</td>
<td>1.36</td>
<td>5.7</td>
<td>Stone1 (0.55), Stone2 (0.51), Thick1 (0.55), Thick2 (0.67)</td>
<td>Thick1 (0.33), Thick2 (0.35), Clay3 (0.26), Clay1 (0.20), Clay2 (0.27), Clay3 (0.23)</td>
</tr>
<tr>
<td>PC5</td>
<td>1.11</td>
<td>4.6</td>
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<td></td>
</tr>
</tbody>
</table>

† The loadings represent the correlation between the variable and the component. Silt1, Silt2, and Silt3 (and similarly for other properties) refer to properties for the upper three horizons (Horizon 1, 2, and 3).
compared best with a combination of the fine earth silt and clay fraction (<50 μm) (Table 4). The composite variable “clay and silt” was significantly different for the “heavy clay” class (6) and the “clay” class (5); the former also contained significantly less sand. The term “heavy” reflected the workability rather than the textural composition per se. The two color indices also related to the local observations (Table 4). Farmers discerned a yellow to red color range and a degree of whiteness and blackness when describing a soil. The yellow to red range related to soil Fe dynamics. The “sand” classes (1, 2, and 7) displayed significant differences for the two color indices. The color white was mainly used in conjunction with clay, and referred to a thin light-colored powdery surface layer that occurred on well-drained clays. The black color was linked to the presence of organic matter. Organic C and N values were highest for soils rich in ironstone and lowest for the Escarpment soils; a somewhat similar tendency was observed for the cation-exchange capacity (CEC) (Table 4).

Similar to the local classification, a classification based on soil texture, color, and ironstone was made for the B horizon (Table 5). The amount of ironstone significantly differed for Class 3, soils having ironstone throughout the profile, and Class 4, soils having ironstone in subsoil, from other classes. Classes 3 and 4 both had higher values for the color indices, and their morphological similarity implied that they could only be separated on the basis of chemical variables (pH, base saturation [BS]). However, land use and management are similar on the two soil classes. Sand content and the RI showed significant differences between Classes 1, 2, and 7. The classes 5B, 6A, and 6B displayed significant differences in clay content; Class 6A had a higher ironstone and lower sand content. Class 6B could be further isolated using the CI and RI. Both RI and CI increased with profile depth; the differentiation between the soil classes was pronounced for CI and even more so for RI values of the B horizon (Tables 4 and 5). Differences between the top- and subsoil are often related to organic C and eluviation processes. Fluctuating water tables influence redox processes in low-lying areas of the landscape. Compared with the topsoil classes, the subsoil classes also displayed a higher level of differentiation in the soil chemical variables. Values for the CEC were highest for Classes 6A and 6B, followed in descending order by Classes 5A, 4, 3, 5B, 1, 2, and 7.

**Comparison with U.S. Soil Taxonomy**

There is a distinct relation between landform and soil according to the local classification and U.S. soil taxonomy (Table 6). Quantifying the local descriptions in terms of soil texture, ironstone, and color indices enabled application of the classification to the subsoil and examining the separation of soil classes, as defined in Table 4 and 5, using multivariate analysis. Cluster analysis was performed on the two first PCs extracted from $R_X$. $R_X$ had a KMO of 0.813, a value of the test statistic for zero correlation of $3128$ ($P < 0.001$), and values for $MS_A > 0.7$. The PC method of factor extraction yielded five independent components according to

---

**Fig. 4. Scatterplots for pedons on the first two principal components according to analysis on X. (I) nonhierarchical multivariate classification, (II) soil morphological classification according to Table 5, (III) great groups of U.S. soil taxonomy.**
criterion Eq. [14], explaining 85.5% of the total variance. Principal Component 1 seemed to be a measure of mineralogy since the most significant loadings are sand, silt, RI, and subsoil ironstone (Table 7). Principal Component 2 had high positive loadings for CI, surface ironstone, and subsoil RI; this component seemed to be a measure of drainage. Principal Component 3 related to mottling color and intensity, PC4 mainly expressed the stoniness, and PC5 was a measure for thickness of the upper horizons. The projection of component scores on the diagram of PC1 vs. PC2 showed a wide scatter with an uneven distribution that could be separated into seven distinct clusters (Fig. 4, I). Along the PC1 axis, soils having a high value for the RI or sand content could be distinguished from soils with high silt contents or high subsoil ironstone content or mottling. Along the PC2 axis, negative values were for soils with a high sand content or poor drainage characteristics (low values for Table 8).

Table 8. Loading values (in parentheses) of soil variables for principal component (PC) analysis performed on the full data set (Y).

<table>
<thead>
<tr>
<th>Axis</th>
<th>Eigen value</th>
<th>% of variance</th>
<th>Strongest positive loadings† (criterion: &gt;0.50 or first 6)</th>
<th>Strongest negative loadings† (criterion: &lt;-0.20 or last 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>15.24</td>
<td>31.10</td>
<td>Silt2 (0.89), Silt1 (0.88), Silt3 (0.84), CEC2 (0.82), CEC1 (0.70), Clay2 (0.68), Clay1 (0.66), Stone3 (0.64), Stone2 (0.62), Stone1 (0.58)</td>
<td>Sand2 (0.95), Sand3 (0.94), Sand1 (0.91), R11 (0.61), R13 (0.50), CI1 (0.46), CI2 (0.42), CI3 (0.39), OC1 (0.36), OC2 (0.33), OC3 (0.30), BS1 (0.26), BS2 (0.23), BS3 (0.20)</td>
</tr>
<tr>
<td>PC2</td>
<td>7.53</td>
<td>15.36</td>
<td>RI2 (0.70), CI1 (0.70), CI3 (0.69), RI1 (0.62), R11 (0.60), R13 (0.56), OC1 (0.56), OC2 (0.51)</td>
<td>pHw1 (0.60), P3 (0.53), pHw2 (0.51), MoCI3 (0.49), P1 (0.46), MoR13 (0.48), P2 (0.45)</td>
</tr>
<tr>
<td>PC3</td>
<td>4.72</td>
<td>9.64</td>
<td>pHK2 (0.71), pHK1 (0.67), pHK3 (0.66), BS3 (0.57), BS2 (0.55), pHw1 (0.53)</td>
<td>pHK2 (0.55), pHK1 (0.48), pHK3 (0.46), BS3 (0.45), BS2 (0.43), BS1 (0.35), pHw1 (0.30), P3 (0.25)</td>
</tr>
<tr>
<td>PC4</td>
<td>3.86</td>
<td>7.87</td>
<td>MoCI2 (0.60), MoR12 (0.60), MoR13 (0.52), Thick2 (0.50), MoCI3 (0.49)</td>
<td>OC1 (0.41), BS2 (0.37), OC3 (0.36), BS3 (0.36), BS1 (0.35), N2 (0.32)</td>
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<tr>
<td>PC5</td>
<td>2.65</td>
<td>5.41</td>
<td>BS1 (0.61), BS2 (0.46), BS3 (0.43), R12 (0.32), CI2 (0.31), CI3 (0.28), R11 (0.31), R13 (0.28)</td>
<td>P2 (0.43), pHK3 (0.40), P3 (0.39), EA1 (0.33), OC1 (0.32), OC3 (0.32)</td>
</tr>
<tr>
<td>PC6</td>
<td>2.20</td>
<td>4.48</td>
<td>P1 (0.51), P2 (0.48), pHw3 (0.47)</td>
<td>SI1 (0.26), SI2 (0.26), SI3 (0.26), SI4 (0.26)</td>
</tr>
<tr>
<td>PC7</td>
<td>1.61</td>
<td>3.28</td>
<td>MoR12 (0.36), MoR13 (0.32), BS3 (0.32)</td>
<td>Stone2 (0.35), Stone3 (0.34), N3 (0.34)</td>
</tr>
<tr>
<td>PC8</td>
<td>1.42</td>
<td>2.89</td>
<td>Thick2 (0.62), Thick1 (0.48)</td>
<td>Thick2 (0.62), Thick1 (0.48)</td>
</tr>
<tr>
<td>PC9</td>
<td>1.20</td>
<td>2.46</td>
<td>EA3 (0.41), OC3 (0.40), pHK1 (0.47)</td>
<td>EA3 (0.41), OC3 (0.40), pHK1 (0.47)</td>
</tr>
<tr>
<td>PC10</td>
<td>1.15</td>
<td>2.34</td>
<td>Thick3 (0.59), P2 (0.29), P1 (0.27)</td>
<td>N1 (0.23), pHw2 (0.21), N2 (0.21)</td>
</tr>
</tbody>
</table>

† The loadings represent the correlation between the variable and the component. Silt1, Silt2, Silt3 (and similarly for other properties) refer to properties for the upper three horizons (Horizon 1, 2, and 3).
Cl), whereas positive values indicated high values for Cl or surface ironstone. As expected, the clusters presented similarities with the soil morphological classification (Fig. 4, II). Some of the soil morphological classes separated well into great groups or subgroups of U.S. soil taxonomy, particularly where the distinctions are associated with soil geomorphic relationships (Fig. 4, III). Cluster 1 represented the red, slightly sticky, sand soils on the Plateau, which are Rhodic Kandiustox. Cluster 2 contained red, sand soils or Ustoxic Quartzipsamments of the Escarpment. Cluster 3 grouped soils high in subsoil ironstone content, whereas Cluster 4 consisted of soils containing plinthite and some subsurface ironstone. Soils having a high silt content and mottling belonged to Cluster 5. These seasonally waterlogged soils of the lowland were classified as “heavy clay” in the local classification and Plinthaquults, Plinthohumults or Plinthustults in U.S. soil taxonomy. Cluster 6 grouped the riverside sand and corresponded with the Oxyaquic Quartzipsamments. Cluster 7 represented soils that are dominated by clay and are fairly well drained; they are clay soils of the upland Interfluve and were classified as Kandiustults.

Results from the PC analysis performed on Y, including the soil chemical variables, showed that the first diagram, PC1 vs. PC2, was more successful in separating soil classes or great groups (Fig. 5). R_Y had a KMO value of 0.735, a test statistic for zero correlation of 5184 (P < 0.001), and large values for MSA. Ten PCs explaining 85% of the total variance were extracted (Table 8). Principal Component 1 contributed to 31.1% of the variance and was strongly dominated by soil texture, CEC, subsurface ironstone, and RI (Table 8). Principal Component 2, representing 15.36% of the variance expressed the soil color (CI, RI), organic C content, and pH. The soil chemical variables pH, BS, and exchangeable acidity (EA), dominated PC3, whereas mottling colors, organic C, and BS correlated strongly with PC4. The loading values of the remaining components were dominated by soil chemical variables, apart from PC7 and PC8 (Table 8). The soil chemical variable CEC contributed to distinguishing the soil classes (Fig. 5, I.A and II.A). The PC3 vs. PC4 diagram (Fig. 5, I.B and II.B) was not successful in separating soil classes. The Duncan-Waller grouping (Tables 4 and 5) provided information that the soil chemical variables, having a high loading on PC3 and PC4, were not significantly different between the soil classes.

CONCLUSIONS

The local soil classification is based on soil texture, ironstone, and soil color of the topsoil to tillage depth, and relates directly to land use and management. Field tests developed for estimating soil texture and amount of ironstone nodules were in accordance with conventional laboratory measurements. Two new color indices, the redness index (RI) and color index (CI), were developed on the basis of Munsell color notation including weighting factors for soil matrix and mottling colors. Analysis of variance techniques and multivariate analysis of soil chemical and morphological variables showed that soil color, soil texture, and ironstone content of both top- and subsoil explained most of the variation of the soils in this tropical case study area. However, the limitation of the soil morphological classification is that it does not have the sufficient chemical information to precisely distinguish between the great groups for exploring potential land use and management strategies, nor does it provide evidence of the generic origin of soils.

Soil texture, occurrence of ironstone, the RI, and the Cl vary with parent material, which in turn is strongly associated with position in the landscape. The implications of our results suggest that digital terrain analysis and subsequent soil-landscape modeling could be useful for predicting the spatial distribution of these easily discernible soil characteristics that relate directly to local land use and management.

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