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# Soil Fertility Status and Its Determining Factors in Tanzania

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## 1. Introduction

The pedogenetic conditions in Tanzania vary widely. In particular, the country has a wide variety of parent materials of soils because of the presence of volcanic mountains, the Great Rift Valley, and several plains and mountains with different elevations (hence, different temperatures). In addition, the amount and seasonal distribution pattern of the annual precipitation vary, from less than 500 mm to more than 2500 mm. The potential land use and agricultural production differ greatly among regions, due to the presence of different soils.

There have been several reports on the distribution patterns of soils and their physicochemical and mineralogical properties. According to a review of the history of soil surveys in Tanzania by Msanya *et al.* (2002), the major soil types described in the country are Ferric, Chromic, and Eutric Cambisols (39.7%); followed by Rhodic and Haplic Ferralsols (13.4%) and Humic and Ferric Acrisols (9.6%). To obtain basic information on soil mineralogy, Araki *et al.* (1998) investigated soil samples collected from regions at different altitudes in the Southern Highland and reported that the cation exchange capacity (CEC) per unit amount of clay content showed a negative correlation with elevation, which was accompanied by clay mineralogical transformation from mica to kaolinite. The authors suggested that soil formation on different planation surfaces is mainly controlled by the geological time factor whereby the lower surfaces are formed at the expense of the higher surfaces. Szilas *et al.* (2005) analyzed the mineralogy of well-drained upland soil samples collected from important agricultural areas in different ecological zones in the sub-humid and humid areas of Tanzania. They concluded that all soils were severely weathered and had limited but variable capacities to hold and release nutrients in plant-available form and to sustain low-input subsistence agriculture. Generally, there seems to be a consensus that the soils in Tanzania and the neighboring countries are not very fertile. The relevance of soil organic carbon management and appropriate fallowing systems such as agroforestry have been pointed out since as critical for sustaining agricultural production (Kimaro *et al.*, 2008; Nandwa, 2001).

In the present study, the regional trend in soil fertility with respect to the soil mineralogical and chemical properties was investigated. Soil properties were correlated with different

pedogenetic factors such as geology and climate. A comprehensive understanding of the distribution of some soil properties as influenced by soil-forming factors is essential for planning an appropriate land-use strategy. Besides, this knowledge will allow developing and sustaining agricultural production, while preserving natural resources such as forest and woodland ecosystems.

## 2. Materials and methods

### 2.1 Soil samples

Ninety-five topsoil samples were collected from different regions of Tanzania. All the sampling points were located on slopes or plains, covering regions with different parent materials and with a wide variety of annual precipitation (less than 250 to more than 1500 mm) (Fig. 1; prepared based on Atlas of Tanzania [1967]). Apparent lowland soils were excluded from the analysis. The parent materials of the soils were broadly classified according to the following categories: (1) volcanic rocks (mostly basic), (2) granite and other plutonic rocks, (3) sedimentary and metamorphic rocks, and (4) Cenozoic rocks and recent deposits. The sampling plots corresponded to croplands or areas covered by either seminatural vegetation (forest or woodland) or secondary vegetation that had grown after human disturbance.

### 2.2 Analytical methods

The soil samples collected were air-dried and passed through a 2-mm mesh sieve. Soil pH in water or 1 mol L<sup>-1</sup> KCl solution was measured with a glass electrode with a 1:5 soil:solution ratio. The pH(NaF) was measured with a glass electrode in 1 mol L<sup>-1</sup> NaF solution after stirring for 2 min; the soil to solution ratio was 1:50. The CEC and the amount of exchangeable bases were measured after extracting with 1 mol L<sup>-1</sup> NH<sub>4</sub>OAc at pH 7.0 and then with a 10% NaCl solution (Thomas, 1982). The NH<sub>4</sub><sup>+</sup> extracted with 10% NaCl solution was distilled after the addition of concentrated NaOH solution, and collected into a 2% H<sub>3</sub>BO<sub>4</sub> solution. Subsequently, the NH<sub>4</sub> content was determined by HCl titration (0.01 mol L<sup>-1</sup>). The exchangeable base (Na, K, Mg, and Ca) content in the NH<sub>4</sub>OAc solution was

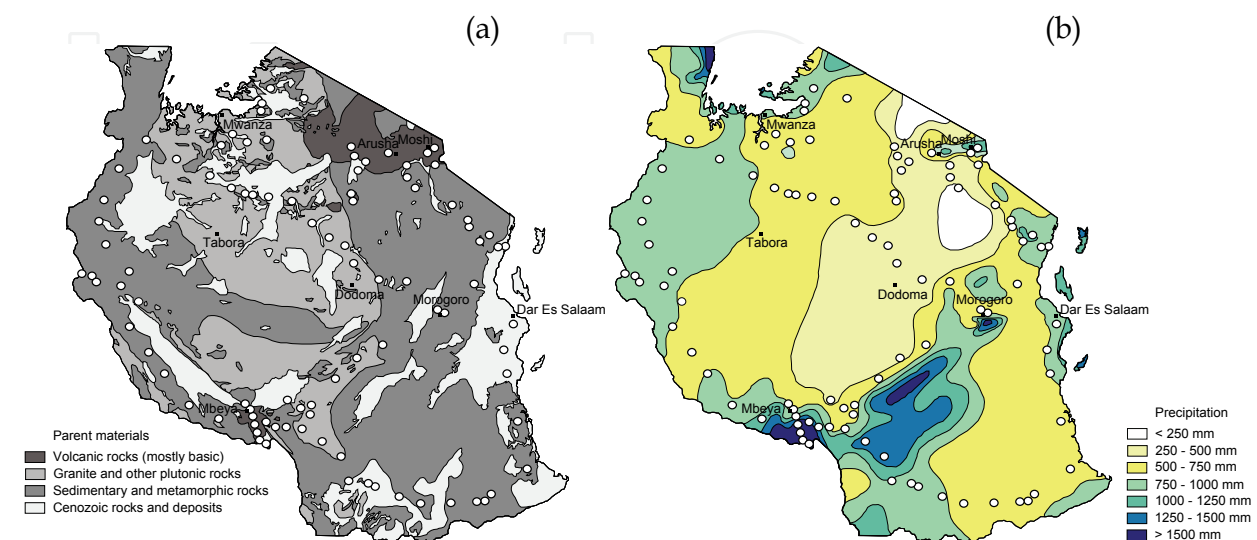


Fig. 1. Geological (a) and climatic (b) conditions of the sampling plots

determined by atomic absorption spectrophotometry (AAS) (Shimadzu, AA-840-01). The exchangeable Al and H were extracted using 1 mol L<sup>-1</sup> KCl. The exchange acidity (Al + H) was determined to pH 8.3 by titration with 0.01 mol L<sup>-1</sup> NaOH wherein phenolphthalein was used as an indicator. Then, after the addition of 4% NaF solution to liberate OH<sup>-</sup> from the Al(OH)<sub>3</sub> precipitates, the exchangeable Al was determined by back titration to obtain the same pH (8.3) using 0.01 mol L<sup>-1</sup> HCl. The exchangeable H content was determined as the difference between the exchange acidity and the exchangeable Al. The total C and total N content were measured with an NC analyzer (Sumigraph NC-800; Sumika Chem. Anal. Service, Ltd., Tokyo, Japan). The available phosphate was determined by the modified Bray-II method (soil:solution = 1:20; shaking time 60s; Bray & Kurz, 1945; Olsen & Sommers, 1982). The particle size distribution was determined using a combination of sieving and pipette methods, in which a complete dispersion of silt and clay particles was achieved by adjusting the pH to 9–10 and supersonication, after pretreatment with H<sub>2</sub>O<sub>2</sub> at 80°C to remove organic matter (Gee & Bauder, 1986). The clay mineral composition was semiquantified by the relative peak areas corresponding to mica (1.0 nm), kaolin minerals (1.0 and 0.7 nm), and expandable 2:1 minerals (1.4 nm) in the X-ray diffractograms obtained by using Cu-K $\alpha$  radiation (RAD-2RS; Rigaku, Tokyo, Japan). The free oxides (Fe, Al, and Si) were extracted by the following two methods: (1) extraction in the dark with acid (pH 3) 0.2 mol L<sup>-1</sup> ammonium oxalate (McKeague & Day, 1966) to obtain Fe<sub>o</sub>, Al<sub>o</sub>, and Si<sub>o</sub> and (2) extraction with a citrate-bicarbonate mixed solution buffered at pH 7.3 by the addition of sodium dithionite (DCB) at 80°C (Mehra & Jackson, 1960) to obtain Fe<sub>d</sub> and Al<sub>d</sub>. The Fe, Al, and Si content in each extract were determined by multi-channel inductively coupled argon plasma atomic emission spectroscopy (ICP-AES) (SPS-1500; Seiko, Chiba, Japan) after filtration of the extracts by 0.45  $\mu$ m Millipore filters.

The data analysis was performed with the software SYSTAT version 8.0 (SPSS, 1998).

### 3. Results and discussion

#### 3.1 Physicochemical and mineralogical properties of the soils

Selected physicochemical and mineralogical properties for the soils studied, and the corresponding statistical analysis, are summarized in Table 1. The surface soils studied were, in general, slightly acidic, with the average values of pH(H<sub>2</sub>O) and pH(KCl) being 6.17 and 5.37, respectively. The exchangeable Al content was low and the base saturation was high, exceeding 95% on average; hence, soil acidity was not considered a serious constraint for agricultural production. Although the average soil texture was sandy clay loam to clay loam, the particle size distribution varied widely. The average C content was 20.7 g kg<sup>-1</sup>, and the dominant clay mineral was kaolinite, followed by clay mica. However, the values obtained for most of the listed properties varied significantly over the regions under study. The coefficients of variation often exceeded 100%; which indicates a significant variability among the soil characteristics for the different regions across Tanzania.

Table 2 summarizes the data obtained, categorized according to the parent materials and land use. In terms of soil parent materials, the physicochemical and mineralogical properties of the volcanic-derived soils ( $n = 12$ ) were significantly different from the other soil groups in terms of CEC, total C content, available P, and free oxide-related properties. Moreover, the proportion of 1.4-nm minerals was significantly higher for the soils originated from Cenozoic rocks or deposits. On the other hand, these soil properties generally did not significantly differ for different land uses.

| Variable  | Number of samples | Ave.(STD)   | Min. -Max. | CV (%) |
|---|-------------------|-------------|------------|--------|
| pH(H <sub>2</sub> O)                                    | 95                | 6.17 (0.80) | 4.36–8.66  | 13.0   |
| pH(KCl)   | 95                | 5.37 (0.89) | 3.71–7.96  | 16.5   |
| pH(NaF)   | 95                | 8.15 (0.66) | 7.12–11.01 | 8.0    |
| EC ( $\mu\text{S dm}^{-1}$ )                            | 95                | 74.3 (59.4) | 10.0–325   | 79.9   |
| CEC ( $\text{cmol}_c \text{ kg}^{-1}$ )                 | 95                | 14.0 (11.0) | 1.61–59.5  | 78.6   |
| Exch. Na ( $\text{cmol}_c \text{ kg}^{-1}$ )            | 95                | 0.18 (0.29) | 0.00–1.92  | 161    |
| Exch. K ( $\text{cmol}_c \text{ kg}^{-1}$ )             | 95                | 1.10 (1.12) | 0.10–5.62  | 102    |
| Exch. Mg ( $\text{cmol}_c \text{ kg}^{-1}$ )            | 95                | 2.78 (2.14) | 0.18–11.4  | 77.0   |
| Exch. Ca ( $\text{cmol}_c \text{ kg}^{-1}$ )            | 95                | 6.98 (8.76) | 0.00–49.5  | 126    |
| Exch. Al ( $\text{cmol}_c \text{ kg}^{-1}$ )            | 95                | 0.21 (0.51) | 0.00–2.99  | 241    |
| Exch. bases ( $\text{cmol}_c \text{ kg}^{-1}$ )         | 95                | 11.0 (11.4) | 0.43–60.7  | 103    |
| Base satur. (%)   | 95                | 95.4 (10.5) | 49.0–101   | 11.0   |
| Sand (%)  | 95                | 63.6 (23.3) | 3.4–96.7   | 36.7   |
| Silt (%)  | 95                | 11.2 (11.3) | 0.2–48.1   | 101    |
| Clay (%)  | 95                | 25.2 (17.6) | 1.5–81.4   | 69.8   |
| Total C ( $\text{g kg}^{-1}$ )                          | 95                | 20.7 (24.4) | 2.13–152   | 124    |
| Total N ( $\text{g kg}^{-1}$ )                          | 95                | 1.49 (1.84) | 0.21–13.7  | 129    |
| Available P ( $\text{gP}_2\text{O}_5 \text{ kg}^{-1}$ ) | 95                | 0.15 (0.24) | 0.01–1.0   | 161    |
| Fe <sub>o</sub> ( $\text{g kg}^{-1}$ )                  | 95                | 2.46 (3.28) | 0.02–14.7  | 133    |
| Al <sub>o</sub> ( $\text{g kg}^{-1}$ )                  | 95                | 3.61 (9.34) | 0.08–64.3  | 259    |
| Si <sub>o</sub> ( $\text{g kg}^{-1}$ )                  | 95                | 1.10 (3.32) | 0.00–21.7  | 303    |
| Fe <sub>d</sub> ( $\text{g kg}^{-1}$ )                  | 95                | 23.7 (25.8) | 0.19–159   | 109    |
| Al <sub>d</sub> ( $\text{g kg}^{-1}$ )                  | 95                | 4.55 (7.48) | 0.01–50.9  | 164    |
| 0.7 nm minerals (%)                                     | 90                | 72.5 (27.0) | 5.4–100    | 37.3   |
| 1.0 nm minerals (%)                                     | 90                | 19.6 (21.4) | 0.0–91.2   | 109    |
| 1.4 nm minerals (%)                                     | 90                | 7.9 (17.9)  | 0.0–94.6   | 227    |

Table 1. Physicochemical and mineralogical properties of the soils studied

### 3.2 Principal component analysis for summarizing soil properties

A principal component analysis was performed to evaluate soil parameters related to soil fertility. The variables selected were pH(H<sub>2</sub>O); pH(KCl); pH(NaF); CEC; amounts of exchangeable Na<sup>+</sup>, K<sup>+</sup>, Mg<sup>2+</sup>, Ca<sup>2+</sup>, and Al<sup>3+</sup>; sand, silt, and clay content; total C and total N content; available P content; and Fe<sub>o</sub>, Al<sub>o</sub>, Si<sub>o</sub>, Fe<sub>d</sub>, and Al<sub>d</sub> content. Table 3 summarizes the factor pattern for the first five principal components after varimax rotation. The analysis resulted in the soil parameters categorized into five principal components, which explained 85.4% of the total variance.

Highly positive coefficients were obtained for pH(NaF), total C and total N,  $Fe_o$ ,  $Al_o$ ,  $Si_o$ , and  $Al_d$  for the first component (Table 3). These variables correspond to the soil properties related to the presence of organic materials that are bound to amorphous compounds, which might be originated on recent volcanic activity. Hence, the first component is referred to as the “soil organic matter (SOM) and amorphous compounds” factor. The second component presents strongly negative coefficients for sand content and highly positive coefficients for clay content, exchangeable Mg, and  $Fe_d$ . These soil characteristics can be related to parent materials and clay formation, i.e. soils derived from mafic and/or clayey parent materials tend to exhibit fine-textured properties with high concentrations of exchangeable Mg and  $Fe_d$  through rapid mineral weathering and clay formation. Hence, the second component is denominated as the “texture” factor. The coefficients corresponding to the third component have highly positive or negative values for pH( $H_2O$ ), pH(KCl), and exchangeable Ca and Al, indicating that a close relationship exists between this component and soil acidity. This relationship can be denominated as the “acidity” factor. The fourth and fifth components are denominated “available P and K” and the “sodicity” factors, respectively, on the basis of the coefficients correlating each of the components and the soil variables (exchangeable K and available P, and exchangeable Na, respectively).

| Variable                       | Averages for soils from different parent materials <sup>1)</sup> |                                  |                                   |                             | Averages for soils under different land uses <sup>1)</sup> |                             |                      |
|--------------------------------|--|----------------------------------|-----------------------------------|-----------------------------|--|-----------------------------|----------------------|
|                                | Volcanic rocks   | Granite and other plutonic rocks | Sedimentary and metamorphic rocks | Cenozoic rocks and deposits | Natural and matured secondary vegetation                   | Incipient fallow vegetation | Cropland             |
| Number of samples              | 12(9) <sup>2)</sup>  | 14                               | 50(48) <sup>2)</sup>              | 19                          | 37(35) <sup>2)</sup>                                       | 16                          | 42(39) <sup>2)</sup> |
| pH( $H_2O$ )                   | 5.91 ab  | 5.70 a                           | 6.28 ab                           | 6.43 b                      | 6.34 a   | 6.14 a                      | 6.04 a               |
| pH(KCl)                        | 5.18 a   | 4.86 a                           | 5.49 a                            | 5.56 a                      | 5.53 a   | 5.32 a                      | 5.26 a               |
| pH(NaF)                        | 9.04 b   | 7.95 a                           | 8.04 a                            | 8.05 a                      | 8.12 a   | 7.99 a                      | 8.22 a               |
| EC ( $\mu S\ dm^{-1}$ )        | 103.2 b  | 48.1 a                           | 78.7 ab                           | 63.9 a                      | 87.2 b   | 35.9 a                      | 77.6 b               |
| CEC ( $cmol_c\ kg^{-1}$ )      | 29.5 b   | 6.93 a                           | 12.5 a                            | 13.3 a                      | 14.3 a   | 8.6 a                       | 15.7 a               |
| Exch. Na ( $cmol_c\ kg^{-1}$ ) | 0.26 ab  | 0.07 a                           | 0.11 a                            | 0.39 b                      | 0.11 a   | 0.12 ab                     | 0.27 b               |
| Exch. K ( $cmol_c\ kg^{-1}$ )  | 2.49 b   | 0.45 a                           | 1.11 a                            | 0.68 a                      | 1.17 a   | 0.70 a                      | 1.19 a               |
| Exch. Mg ( $cmol_c\ kg^{-1}$ ) | 4.34 b   | 1.25 a                           | 2.70 ab                           | 3.12 b                      | 2.95 a   | 2.53 a                      | 2.72 a               |

| Variable   | Averages for soils from different parent materials <sup>1)</sup> |                                  |                                   |                             | Averages for soils under different land uses <sup>1)</sup> |                             |          |
|--|--|----------------------------------|-----------------------------------|-----------------------------|--|-----------------------------|----------|
|  | Volcanic rocks   | Granite and other plutonic rocks | Sedimentary and metamorphic rocks | Cenozoic rocks and deposits | Natural and matured secondary vegetation                   | Incipient fallow vegetation | Cropland |
| Exch. Ca (cmol <sub>c</sub> kg <sup>-1</sup> )                 | 11.60 b  | 1.68 a                           | 5.87 ab                           | 10.85 b                     | 8.02 a   | 4.17 a                      | 7.13 a   |
| Exch. Al (cmol <sub>c</sub> kg <sup>-1</sup> )                 | 0.18 a   | 0.28 a                           | 0.25 a                            | 0.07 a                      | 0.22 a   | 0.28 a                      | 0.18 a   |
| Exch. bases (cmol <sub>c</sub> kg <sup>-1</sup> )              | 18.7 b   | 3.4 a                            | 9.8 ab                            | 15.0 b                      | 12.2 a   | 7.5 a                       | 11.3 a   |
| Base satur. (%)  | 97.4 ab  | 88.5 a                           | 95.4 ab                           | 99.0 b                      | 96.5 a   | 92.3 a                      | 95.5 a   |
| Sand (%)   | 36.2 a   | 73.9 b                           | 64.7 b                            | 70.2 b                      | 66.2 a   | 69.0 a                      | 59.1 a   |
| Silt (%)   | 28.7 b   | 6.6 a                            | 9.2 a                             | 9.0 a                       | 9.5 a  | 7.0 a                       | 14.3 a   |
| Clay (%)   | 35.1 a   | 19.5 a                           | 26.1 a                            | 20.8 a                      | 24.3 a   | 23.9 a                      | 26.5 a   |
| Total C (g kg <sup>-1</sup> )                                  | 43.3 b   | 12.5 a                           | 20.1 a                            | 13.9 a                      | 28.4 a   | 11.8 a                      | 17.2 a   |
| Total N (g kg <sup>-1</sup> )                                  | 3.40 b   | 0.98 a                           | 1.42 a                            | 0.87 a                      | 1.98 a   | 0.80 a                      | 1.33 a   |
| Available P (gP <sub>2</sub> O <sub>5</sub> kg <sup>-1</sup> ) | 0.431 b  | 0.044 a                          | 0.128 a                           | 0.112 a                     | 0.154 a  | 0.067 a                     | 0.180 a  |
| Fe <sub>o</sub> (g kg <sup>-1</sup> )                          | 8.35 b   | 0.73 a                           | 2.04 a                            | 1.12 a                      | 2.26 a   | 1.11 a                      | 3.16 a   |
| Al <sub>o</sub> (g kg <sup>-1</sup> )                          | 13.89 b  | 1.50 a                           | 2.76 a                            | 0.91 a                      | 4.22 a   | 1.11 a                      | 4.02 a   |
| Si <sub>o</sub> (g kg <sup>-1</sup> )                          | 4.83 b   | 0.16 a                           | 0.75 a                            | 0.34 a                      | 1.18 a   | 0.29 a                      | 1.33 a   |
| Fe <sub>d</sub> (g kg <sup>-1</sup> )                          | 40.2 b   | 13.2 a                           | 26.5 ab                           | 11.4 a                      | 23.2 a   | 26.2 a                      | 23.1 a   |
| Al <sub>d</sub> (g kg <sup>-1</sup> )                          | 11.34 b  | 3.50 a                           | 4.37 a                            | 1.50 a                      | 5.58 a   | 2.98 a                      | 4.24 a   |
| 0.7 nm minerals (%)  | 75.8 a   | 80.4 a                           | 73.3 a                            | 63.0 a                      | 73.9 a   | 79.6 a                      | 68.3 a   |
| 1.0 nm minerals (%)  | 20.1 a   | 13.8 a                           | 22.0 a                            | 17.8 a                      | 20.9 a   | 16.1 a                      | 19.9 a   |
| 1.4 nm minerals (%)  | 4.2 a  | 5.8 a                            | 4.7 a                             | 19.2 b                      | 5.2 a  | 4.3 a                       | 11.8 a   |

<sup>1)</sup> The values with the same letters are not significantly different by Tukey test ( $p < 0.05$ ).

<sup>2)</sup> Parenthesis denotes the number of samples considered for XRD analysis (i.e. the percentage of 0.7, 1.0 and 1.4 nm minerals). Some samples were excluded from the analysis because of their X-ray amorphous natures.

Table 2. Average values of measured soil variables in terms of parent materials or land uses

| Variable             | PC1  | PC2                 | PC3                 | PC4                           | PC5                  |
|----------------------|--|---------------------|---------------------|-------------------------------|----------------------|
| pH(H <sub>2</sub> O) | -0.19                                      | -0.07               | -0.94               | 0.10                          | 0.04                 |
| pH(KCl)              | -0.05                                      | -0.11               | -0.95               | 0.10                          | -0.02                |
| pH(NaF)              | 0.84                                       | 0.00                | -0.05               | 0.29                          | 0.05                 |
| CEC                  | 0.57                                       | 0.51                | -0.09               | 0.39                          | 0.43                 |
| Exch. Na             | -0.01                                      | -0.01               | 0.04                | 0.08                          | 0.93                 |
| Exch. K              | 0.01                                       | 0.32                | -0.29               | 0.84                          | 0.07                 |
| Exch. Mg             | -0.03                                      | 0.62                | -0.42               | 0.36                          | 0.39                 |
| Exch. Ca             | 0.05                                       | 0.28                | -0.64               | 0.38                          | 0.47                 |
| Exch. Al             | 0.20                                       | 0.12                | 0.64                | -0.08                         | 0.07                 |
| Sand                 | -0.30                                      | -0.83               | -0.11               | -0.35                         | -0.17                |
| Silt                 | 0.45                                       | 0.29                | 0.05                | 0.65                          | 0.21                 |
| Clay                 | 0.11                                       | 0.91                | 0.11                | 0.04                          | 0.09                 |
| Total C              | 0.89                                       | 0.20                | 0.08                | 0.02                          | 0.01                 |
| Total N              | 0.88                                       | 0.19                | 0.14                | 0.03                          | 0.01                 |
| Avail. P             | 0.06                                       | 0.02                | -0.26               | 0.87                          | 0.04                 |
| Fe <sub>o</sub>      | 0.62                                       | 0.32                | 0.18                | 0.57                          | -0.01                |
| Al <sub>o</sub>      | 0.97                                       | 0.00                | 0.13                | 0.05                          | 0.01                 |
| Si <sub>o</sub>      | 0.94                                       | -0.07               | 0.07                | 0.10                          | 0.04                 |
| Fe <sub>d</sub>      | 0.09                                       | 0.86                | 0.15                | 0.13                          | -0.27                |
| Al <sub>d</sub>      | 0.87                                       | 0.24                | 0.26                | -0.06                         | -0.08                |
| Eigenvalue           | 5.98                                       | 3.43                | 3.14                | 2.92                          | 1.60                 |
| Proportion (%)       | 29.9                                       | 17.2                | 15.7                | 14.6                          | 8.0                  |
|                      | "SOM and<br>amorphous<br>compounds" factor | "Texture"<br>factor | "Acidity"<br>factor | "Available P<br>and K" factor | "Sodicity"<br>factor |

Table 3. Factor pattern for the first four principal components ( $n = 95$ )

### 3.3 Pedogenetic conditions determining the distribution patterns of factor scores for each of the principal components

Figure 2 shows a scattergram of the factor scores of SOM and amorphous compounds and those of available P and K. Both factor scores were significantly higher in soils derived from volcanic rocks than in other soils, but no significant correlation was observed. The factor scores are plotted on the geological map, as shown in Figure 3. There are two representative volcanic areas in Tanzania, namely, Mount. Kilimanjaro and the surrounding region and the southern mountain ranging between the east of Mbeya and Lake Malawi. Generally, the scores of the factor for SOM and amorphous compounds were highest in the region of the southern volcanic mountain ranges, followed by some plots around Mt. Kilimanjaro (Fig. 3a), whereas the scores of the factor for available P and K tended to be high in both volcanic



regions (Fig. 3b). Msanya *et al.* (2007) indicated that the volcanic soils in the southern mountain ranges were rich in K, compared to several Japanese volcanic soils, most likely reflecting lithological differences among the parent materials. The predominantly high scores of the factor for SOM and amorphous compounds in the southern volcanic mountain ranges indicate a relatively incipient feature of soils after recent active volcanic events and potentially high soil fertility relating to SOM in these regions. In addition, soils located in those volcanic regions could be more fertile in terms of P and K nutrients supply from soils.

Figure 3c represents the distribution pattern of the factor scores of texture in terms of the geological conditions. There is a certain regional trend in these factor scores, though no statistical difference was observed in terms of the geological condition as a whole. Among the soils of volcanic origin, those in the northern volcanic regions exhibited higher scores in the texture factor, consistent with a previous report by Mizota *et al.* (1988), in which they postulated that these soils were in the advanced stages of weathering of volcanic materials. The scores were high for some soils originated from sedimentary and metamorphic rocks, which are mostly distributed in the western region around Kigoma and the hill slopes near Tanga. Otherwise, scores were in general low for soils originated from granite, except for those of the southern highland.

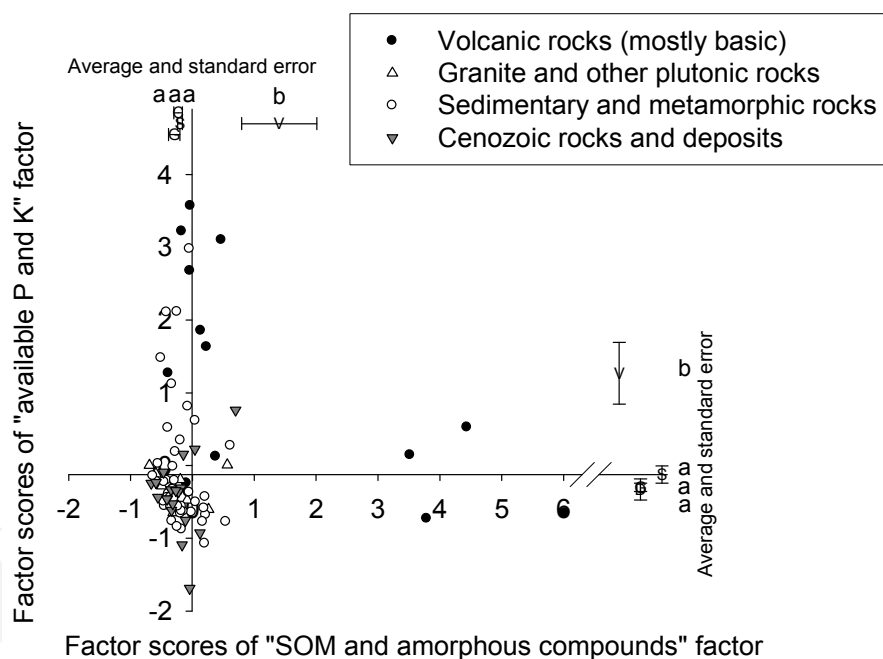


Fig. 2. Relationship between the scores of the "SOM and amorphous" and "available P and K" factors

Figure 4 shows the influence of the amount of precipitation on the scores of selected factors. There was no significant relationship between the amount of precipitation and the factor scores of acidity or texture. Although the positive contribution of precipitation on mineral weathering might accompany soil acidification or the formation of clays and secondary Fe oxides, there was no correlation between those processes, which indirectly suggests that the influence of parent materials on soil properties is stronger than climatic factors among the soils studied.

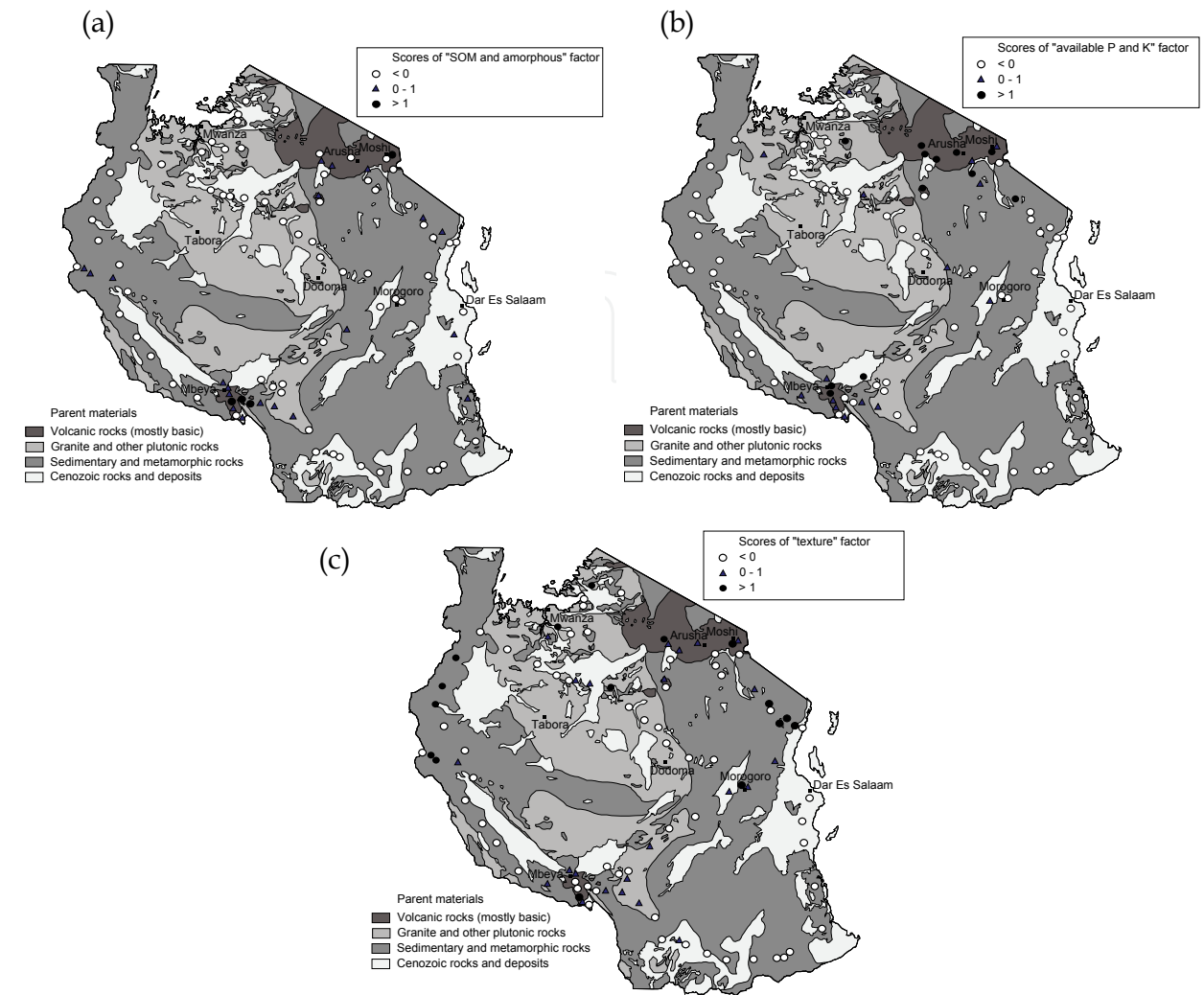


Fig. 3. Distribution patterns of scores of (a) "SOM and amorphous," (b) "available P and K," and (c) "texture" factors in relation to geological conditions

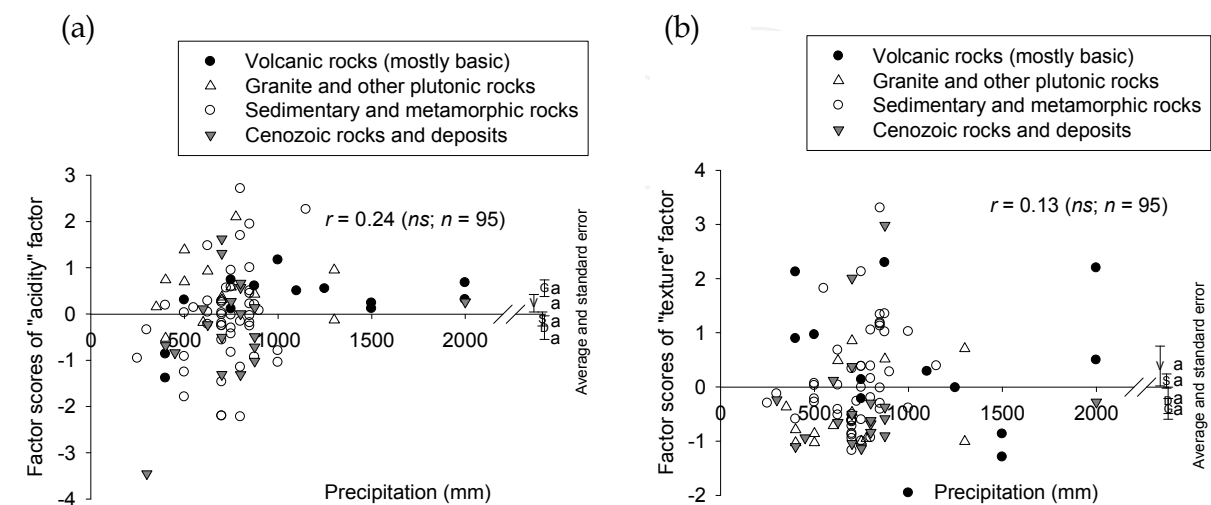


Fig. 4. Relationships between precipitation and scores of (a) "acidity" and (b) "texture" factor

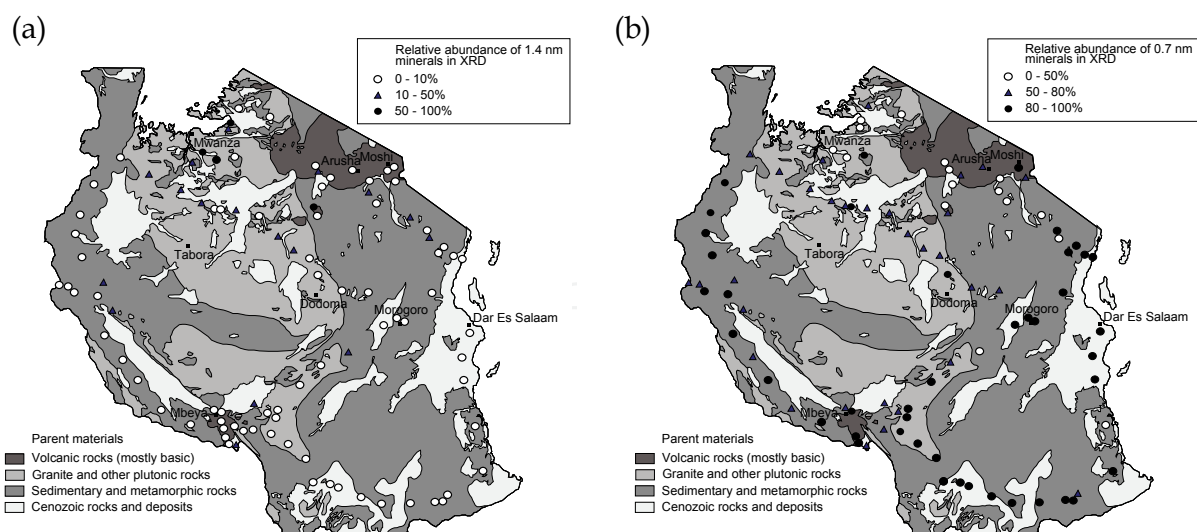


Fig. 5. Distribution patterns of clay mineralogy in relation to geological or climatic conditions. Abundances of (a) 1.4 nm and (b) 0.7 nm minerals

### 3.4 Pedogenetic conditions determining the clay mineralogy of the soils

Figure 5 shows the distribution patterns of the clay mineralogy in relation to the geological and climatic conditions. The relative abundance of 1.4-nm minerals was often higher in the northern region of the Great Rift Valley and around Lake Victoria. On the other hand, the abundance of 0.7-nm minerals tended to be lower in the central steppe, which has lower precipitation than other regions. These relationships are more clearly presented in Figure 6. Stepwise multiple regression indicated that the abundances of 1.4-nm minerals (mostly smectite) could be expressed by the following equation:

$$1.4\text{-nm minerals (\%)} = 6.38 + 13.4 (\text{sodicity factor}) - 9.78 (\text{SOM / amorphous factor}) + 3.17 (\text{P / K factor}); \quad r^2 = 0.58 \quad (p < 0.01, n = 90) \quad (1)$$

The 1.4-nm minerals were probably formed under the strong influence of the high sodicity of the parent materials around the Great Rift Valley, and were often observed in the soils in the flat plains near Lake Victoria.

On the other hand, the abundances of the 0.7-nm minerals (kaolin minerals) can be expressed by the following equation:

$$0.7\text{-nm minerals (\%)} = -56.2 + 19.5 \ln(\text{precipitation in mm}) + 5.92(\text{acidity factor}) + 4.82 (\text{texture factor}) - 11.2 (\text{sodicity factor}) - 7.70 (\text{P / K factor}); \quad r^2 = 0.45 \quad (p < 0.01, n = 90) \quad (2)$$

From this equation, it can be stated that the kaolin formation is promoted under highly humid conditions with the positive influence of soil acidity and texture (or clayey parent materials) as well as the negative influence of sodicity. Hence, it can be inferred that the clay mineralogical properties of the soils studied herein were formed under the strong influence of the present climatic conditions as well as the parent materials on a countrywide scale in Tanzania.

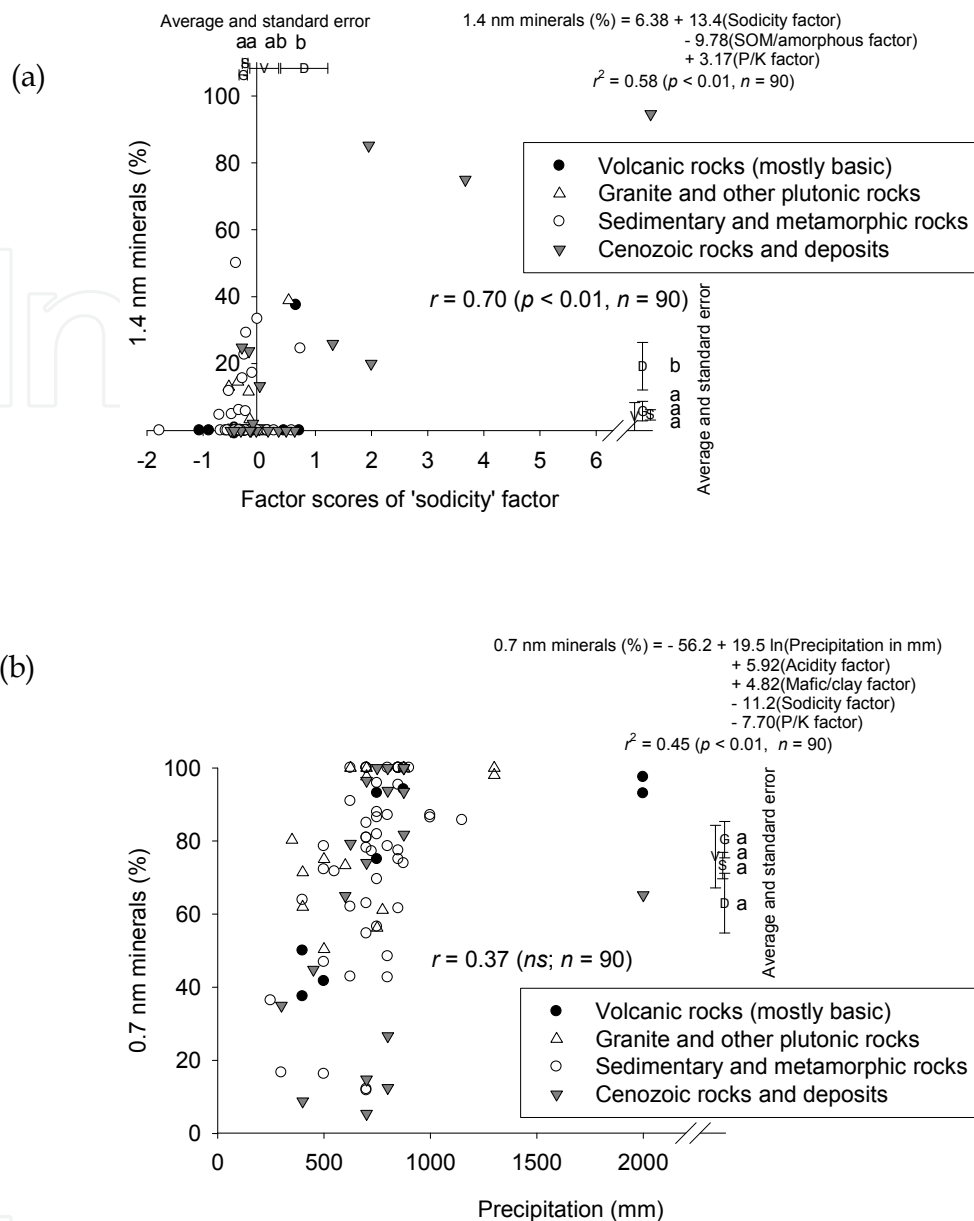


Fig. 6. Relationships between clay mineralogy and soil and climatic factors. Abundances of (a) 1.4 nm and (b) 0.7 nm minerals

### 3.5 General discussion on the soil conditions in Tanzania with specific reference to potential agricultural development

As previously stated, soils can be considered as significantly fertile in the volcanic regions and areas around, due to the high SOM contents and the high P and K nutrient status. In addition, the soils around Lake Victoria are fertile due to the strong influence of the 1.4-nm minerals, which contributes to the retention of base cations. Both regions, namely, the volcanic regions and the regions around Lake Victoria, are included in the Great Rift Valley, which is the center of intensive agricultural activities of the country. However, in other areas of Tanzania, soils are generally low in SOM-related parameters and the 1.4-nm minerals are virtually absent, presumably due to consecutive mineral weathering under ustic soil moisture regime (Watanabe *et al.*, 2006). The proportion of kaolin minerals increases with

the precipitation; hence, soil fertility decreases in regions of high humidity. Soil fertility in terms of clay mineralogy is comparatively higher in dry regions than in humid regions because of the greater abundance of mica minerals. However, water availability decreases in such dry regions. Thus, the semiarid regions in Tanzania suffer from water scarcity, while the relatively humid areas have less fertile soil that predominantly contains kaolin minerals. In summary, high scores in SOM-related properties and the 1.4-nm minerals contribute to relatively high soil fertility in Great Rift Valley regions, whereas either water scarcity or low soil fertility are not favorable for agricultural production in the other regions of Tanzania. These conditions should be considered when studying the feasibility of agricultural development in different areas in the future.

#### 4. Conclusion

From the principal component analysis of the collected soil samples, five individual factors—SOM and amorphous compounds, texture, acidity, available P and K, and sodicity—were determined which explained 85.4% of total variance. From the clay mineralogical composition and the relation between the geological conditions (or parent materials) and the annual precipitation and the scores of the five factors, the following conclusions can be summarized:

1. The maximum scores of “SOM and amorphous compounds” were found at the volcanic center of the southern mountain ranges from the east of Mbeya to Lake Malawi.
2. The scores of the “available P and K” were high in the volcanic regions around Mt. Kilimanjaro and in the southern volcanic mountain ranges.
3. The abundance of 1.4-nm minerals (mostly smectite) can be expressed by the following equation (Equation 1):

$$1.4\text{-nm minerals (\%)} = 6.38 + 13.4 (\text{sodicity factor}) - 9.78 (\text{SOM / amorphous factor}) + 3.17 (\text{P / K factor}); \quad r^2 = 0.58 (p < 0.01, n = 90)$$

The 1.4-nm minerals were probably formed under conditions of high sodicity and were often observed in the soils near Lake Victoria.

4. The abundance of 0.7-nm minerals (kaolin minerals) can be expressed by the following equation (Equation 2):

$$0.7\text{-nm minerals (\%)} = -56.2 + 19.5 \ln(\text{precipitation in mm}) + 5.92 (\text{acidity factor}) + 4.82 (\text{texture factor}) - 11.2 (\text{sodicity factor}) - 7.70 (\text{P / K factor}); \\ r^2 = 0.45 (p < 0.01, n = 90)$$

Equation 2 suggests that kaolin formation is promoted under highly humid conditions, which is also controlled by the acidity and texture of the soil (or parent materials). Hence, the results indicate that the formation of the soils studied in the present study was strongly influenced by climatic conditions and parent materials.

5. In Tanzania, the volcanic regions and the Great Rift Valley region, where soil is generally more fertile than in other regions, are favorable to modernized agriculture. The semiarid regions in Tanzania suffer from water scarcity, while the relatively humid areas have less fertile soil that predominantly contains kaolin minerals. These

conditions are not favorable for agricultural production and must be strongly considered when studying the feasibility of agricultural development in different areas in the future.

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## **Soil Health and Land Use Management**

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Soils play multiple roles in the quality of life throughout the world, not only as the resource for food production, but also as the support for our structures, the environment, the medium for waste disposal, water, and the storage of nutrients. A healthy soil can sustain biological productivity, maintain environmental quality, and promote plant and animal health. Understanding the impact of land management practices on soil properties and processes can provide useful indicators of economic and environmental sustainability. The sixteen chapters of this book orchestrate a multidisciplinary composition of current trends in soil health. Soil Health and Land Use Management provides a broad vision of the fundamental importance of soil health. In addition, the development of feasible management and remediation strategies to preserve and ameliorate the fitness of soils are discussed in this book. Strategies to improve land management and relevant case studies are covered, as well as the importance of characterizing soil properties to develop management and remediation strategies. Moreover, the current management of several environmental scenarios of high concern is presented, while the final chapters propose new methodologies for soil pollution assessment.

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