Chapter 4
Soil-Forming Factors Determining the Distribution Patterns of Different Soils in Tanzania with Special Reference to Clay Mineralogy

Shinya Funakawa and Method Kilasara

Abstract Soil-forming conditions in Tanzania, which is located near the Great Rift Valley, vary with geological and climatic conditions. In the present study, 95 surface soil samples were collected from croplands, forests, and savannas in different regions across Tanzania and the physicochemical and mineralogical properties of the samples were analyzed. Reflecting the wide variation of climatic conditions and parent materials of soils, soil physicochemical properties varied widely. Clay mineral composition was basically similar to the soils developed under ustic moisture regime in Southeast Asia, in which mica and kaolin minerals were usually dominated. Based on a principal component analysis of the collected soil samples, five individual factors were determined. 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 observations were made: (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, presumably due to the intensive agricultural management with fertilizer application. (3) The 1.4-nm minerals were probably formed under conditions of high sodicity and were often observed in the soils near Lake Victoria. (4) In Tanzania, the volcanic regions and the Great Rift Valley region, where soil is generally more fertile than in other regions, are conducive to modernized agriculture. The semiarid regions in Tanzania suffer from water shortage, while the relatively humid areas have less fertile soil that predominantly contains kaolin minerals. These conditions are not favorable for agricultural production and should be taken into consideration

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S. Funakawa (ed.), *Soils, Ecosystem Processes, and Agricultural Development*,
DOI 10.1007/978-4-431-56484-3_4

when studying the feasibility of agricultural development in different areas in the future.

Keywords Clay mineralogy • Great Rift Valley • Soil fertility • Tanzania

4.1 Introduction

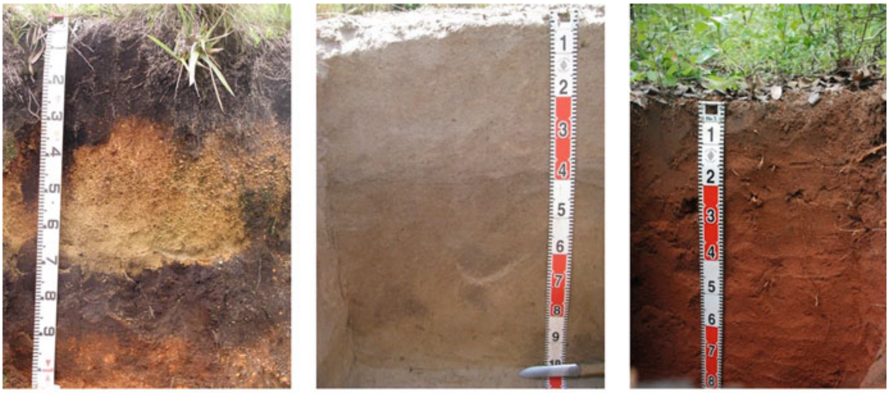
The pedogenetic conditions in Tanzania vary widely. In particular, the country has a wide variety of parent materials of soils because of the presence of volcanic mountains, the Great Rift Valley, and several plains and mountains with different elevations (hence, different temperatures). In addition, 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, owing 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 soils observed in the country are ferric, chromic, and eutric Cambisols (39.7 %); these are 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 controlled mainly 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 subhumid and humid parts 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 its neighboring countries are not very fertile. According to the Global Soil Regions (Soil Survey Staff, 1999), distribution pattern of soils in East Africa may summarized by the dominance of Ultisols and Alfisols with accessorized distribution of Aridisols and Oxisols.

In the present study, the regional trend in soil fertility was investigated with special reference to the clay mineralogy and its forming conditions such as geology and climate. An understanding of why the distribution of some soil properties is influenced by soil-forming factors would help in planning an appropriate land-use strategy, which should make it possible to not only sustain and develop agricultural production but also maintain natural resources such as forest and woodland ecosystems.

4.2 Soil Samples and Analytical Procedure

Ninety-five samples of surface soils were collected from different regions of Tanzania (Figs. 4.1 and 4.2). 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. 4.2; 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 were used as croplands or were covered by



a) Andisols in Kipengere range

b) Entisols (Arenosols) in Morogoro region

c) Ultisols (Acrisols) in Ruvuma region

d) Alfisols (Lixisols) in Dodoma region

e) Vertisols in Arusha region

f) Inceptisols (Nitisols) in surrounding area of volcanic region

Fig. 4.1 Representative soil profiles observed in Tanzania

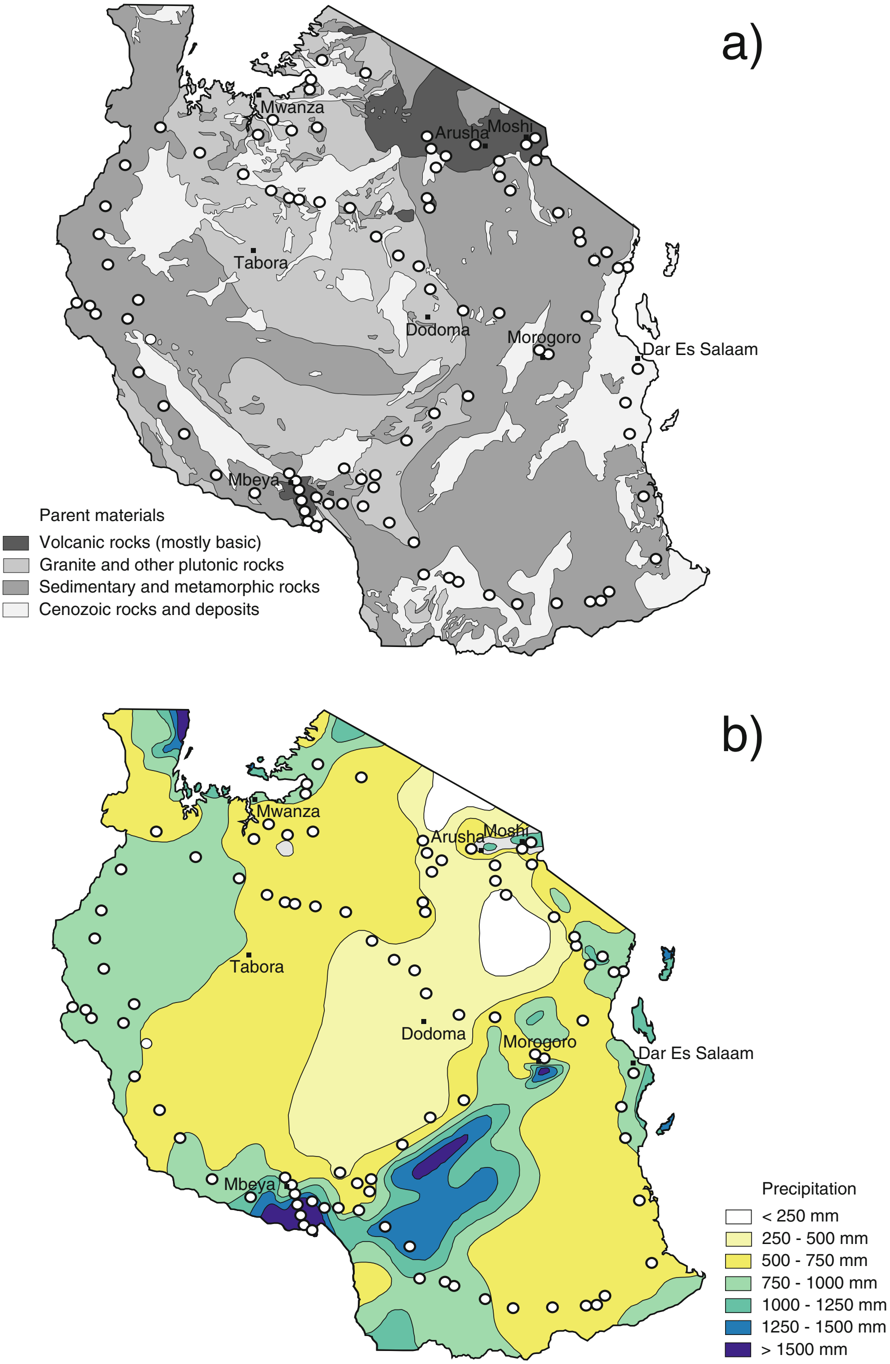


Fig. 4.2 Geological and climatic conditions of the sampling plots

seminatural vegetation (forest or woodland) or secondary vegetation that had grown after human disturbance.

The chemical and mineralogical properties of the samples were analyzed; we determined the pH(H_2O), pH(KCl), electrical conductivity (EC), exchangeable cations (bases and Al), cation exchange capacity (CEC), total C and total N content, available P (Bray-II method), particle size distribution, acid ammonium oxalate- and DCB-extractable oxides (Fe_o, Al_o, Si_o, Fe_d, and Al_d), and clay mineral composition (by X-ray diffraction). The data obtained were statistically analyzed with the software SYSTAT version 8.0 (SPSS 1998).

4.3 General Physicochemical and Mineralogical Properties of the Soils

Selected statistical values of the analytical data are listed in Table 4.1. The surface soils studied were usually slightly acidic, with the average values of pH(H_2O) 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^{-1}. However, the obtained values of most of the aforementioned variables varied significantly over the regions under study, with their coefficients of variation exceeding 100 %; these results indicated a marked difference in the soil characteristics in various regions across Tanzania.

According to the X-ray analysis, several patterns of diffractograms were obtained (Fig. 4.3a–d); the dominant clay mineral was kaolinite, followed by clay mica. In the volcanic centers in the northern and southern mountains, X-ray amorphous clays from volcanic origin were observed. The 1.4-nm clay minerals such as smectite were occasionally dominated among the soils from northwestern region of the country. Figure 4.3e shows a summary of semiquantitative clay mineral composition of all the soils studied, except for the volcanic soils with X-ray amorphous. Although some soils developed on Cenozoic rocks and recent deposits contained fairly high amounts of expandable 1.4-nm minerals, the majority of the soils were dominated by mica and kaolin minerals with few amounts of 1.4-nm minerals. This composition was basically similar to that of the Asian soils developed under ustic soil moisture regime (Chap. 3 in this volume; Funakawa et al. 2008), indicating that the mineral weathering pathways postulated for the Asian soils could be applicable to Tanzanian soils under ustic soil moisture regime.

Table 4.2 lists the obtained data 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 unique; they were significantly different from the other soil groups in terms of CEC, total C content,

Table 4.1 Descriptive statistics for the physicochemical and mineralogical properties of the soils studied

Variable	Number of samples	Average	Minimum	Maximum	Standard deviation	Coefficient of variation (%)
pH(H_2O)	95	6.17	4.36	8.66	0.80	13.0
pH(KCl)	95	5.37	3.71	7.96	0.89	16.5
pH(NaF)	95	8.15	7.12	11.01	0.66	8.0
EC(μS dm^{-1})	95	74.3	10.0	325	59.4	79.9
CEC ($cmol_c$ kg^{-1})	95	14.0	1.61	59.5	11.0	78.6
Exch. Na ($cmol_c$ kg^{-1})	95	0.18	0.00	1.92	0.29	161
Exch. K ($cmol_c$ kg^{-1})	95	1.10	0.10	5.62	1.12	102
Exch. Mg ($cmol_c$ kg^{-1})	95	2.78	0.18	11.4	2.14	77.0
Exch. Ca ($cmol_c$ kg^{-1})	95	6.98	0.00	49.5	8.76	126
Exch. Al ($cmol_c$ kg^{-1})	95	0.21	0.00	2.99	0.51	241
Exch. bases ($cmol_c$ kg^{-1})	95	11.0	0.43	60.7	11.4	103
Base satur. (%)	95	95.4	49.0	101	10.5	11.0
Sand (%)	95	63.6	3.4	96.7	23.3	36.7
Silt (%)	95	11.2	0.2	48.1	11.3	101
Clay (%)	95	25.2	1.5	81.4	17.6	69.8
Total C (g kg^{-1})	95	20.7	2.13	152	24.4	124
Total N (g kg^{-1})	95	1.49	0.21	13.7	1.84	129
Available P (gP_2O_5 kg^{-1})	95	0.15	0.01	1.0	0.24	161
Fe_o (g kg^{-1})	95	2.46	0.02	14.7	3.28	133
Al_o (g kg^{-1})	95	3.61	0.08	64.3	9.34	259
Si_o (g kg^{-1})	95	1.10	0.00	21.7	3.32	303
Fe_d (g kg^{-1})	95	23.7	0.19	159	25.8	109
Al_d (g kg^{-1})	95	4.55	0.01	50.9	7.48	164
0.7 nm minerals (%)	90	72.5	5.4	100	27.0	37.3
1.0 nm minerals (%)	90	19.6	0.0	91.2	21.4	109
1.4 nm minerals (%)	90	7.9	0.0	94.6	17.9	227

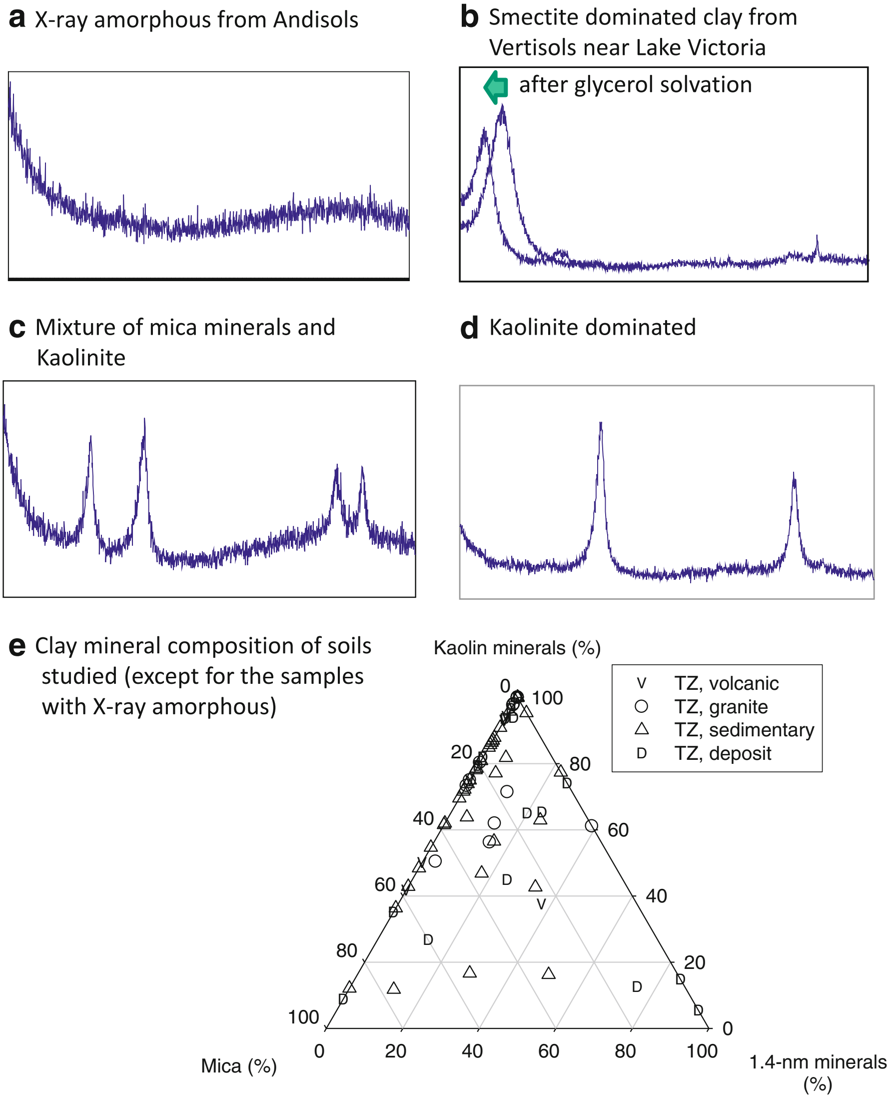


Fig. 4.3 Representative patterns of X-ray diffractograms of clay specimen (**a**–**d**) and summary of semi-quantitive clay mineral composition of all the soils studied (**e**)

available P, and free oxide-related properties. On the other hand, these soil properties usually did not differ significantly for different land uses.

A principal component analysis was conducted to summarize several soil parameters related to soil fertility. The studied variables included pH(H_2O); pH (KCl); pH(NaF); CEC; amounts of exchangeable Na^+, K^+, Mg^{2+}, Ca^{2+}, and Al^{3+};

Table 4.2 Average values of measured soil variables in terms of parent materials or land uses

	Averages for soils from different parent materials				Averages for soils under different land uses		
Variable	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)[a)]	14	50(48)[a)]	19	37(35)[a)]	16	42(39)[a)]
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 (μS 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 (cmolc 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 (cmolc 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 (cmolc kg^{-1})	4.34 b	1.25 a	2.70 ab	3.12 b	2.95 a	2.53 a	2.72 a
Exch. Ca (cmolc kg^{-1})	11.60 b	1.68 a	5.87 ab	10.85 b	8.02 a	4.17 a	7.13 a
Exch. Al (cmolc kg^{-1})	0.18 a	0.28 a	0.25 a	0.07 a	0.22 a	0.28 a	0.18 a
Exch. bases ($cmol_c$ kg^{-1})	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^{-1})	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^{-1})	3.40 b	0.98 a	1.42 a	0.87 a	1.98 a	0.80 a	1.33 a
Available P (gP_2O_5 kg^{-1})	0.431 b	0.044 a	0.128 a	0.112 a	0.154 a	0.067 a	0.180 a
Fe_o (g kg^{-1})	8.35 b	0.73 a	2.04 a	1.12 a	2.26 a	1.11 a	3.16 a
Al_o (g kg^{-1})	13.89 b	1.50 a	2.76 a	0.91 a	4.22 a	1.11 a	4.02 a
Si_o (g kg^{-1})	4.83 b	0.16 a	0.75 a	0.34 a	1.18 a	0.29 a	1.33 a
Fe_d (g kg^{-1})	40.2 b	13.2 a	26.5 ab	11.4 a	23.2 a	26.2 a	23.1 a
Al_d (g kg^{-1})	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

[a] Parenthesis denotes the number of samples for XRD analysis (i.e., the percentage of 0.7, 1.0, and 1.4 nm minerals)

Table 4.3 Factor pattern for the first four principal components ($n = 95$)

Variable	PC1	PC2	PC3	PC4	PC5
pH(H_2O)	−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_o	0.62	0.32	0.18	0.57	−0.01
Al_o	0.97	0.00	0.13	0.05	0.01
Si_o	0.94	−0.07	0.07	0.10	0.04
Fe_d	0.09	0.86	0.15	0.13	−0.27
Al_d	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 amorphous compounds" factor	"Texture" factor	"Acidity" factor	"Available P and K" factor	"Sodicity" factor

sand, silt, and clay content; total C and total N content; available P content; and Fe_o, Al_o, Si_o, Fe_d, and Al_d content. Table 4.3 lists the factor pattern for the first five principal components after varimax rotation.

As seen from the list in Table 4.3, high 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. These variables correspond to the properties derived from organic materials that are bound to amorphous compounds, which might have originated from recent volcanic activity. Hence, the first component is referred to as the "soil organic matter (SOM) and amorphous compounds" factor. The second component has high negative coefficients for sand content and high positive coefficients for clay content, exchangeable Mg, and Fe_d. These soil characteristics could be associated with parent materials and clay formation, that is, 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 referred to as the "texture" factor. The coefficients corresponding to the third component have high 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 referred to as the "acidity" factor. The fourth and fifth components are referred to as the "available P and K" and the "sodicity" factors, respectively, on the basis of the coefficients correlating each of the components and the soil variables.

4.4 Principal Component Analysis for Summarizing Soil Properties

From this analysis, a wide variety of soil parameters were categorized into five principal components, which accounted for 85.4 % of the total variance.

4.5 Pedogenetic Conditions Determining the Distribution Patterns of Factor Scores for Each of the Principal Components

Figure 4.4 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 they were not statistically correlated. The factor scores are plotted on the geological map, as shown in Fig. 4.5. There are two representative volcanic areas in Tanzania, namely, Mt. Kilimanjaro and its surrounding region and Kipengere range 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 Kipengere range, followed by some plots around Mt. Kilimanjaro (Fig. 4.5a), whereas the scores of the factor for available P and K tended to be high in both volcanic regions (Fig. 4.5b). Since these regions were already cultivated intensively, influence of chemical fertilizer might affect the high scores in this factor. Furthermore, as Msanya et al. (2007) indicated, the volcanic soils in the southern mountain ranges were rich in K, compared to several Japanese volcanic soils, likely reflecting lithological differences among the parent materials. The predominantly high scores of the factor for SOM and amorphous compounds in Kipengere range indicate a relatively incipient feature of soils after recent active volcanic events and potentially high soil fertility relating to SOM in these regions.

Figure 4.5c 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

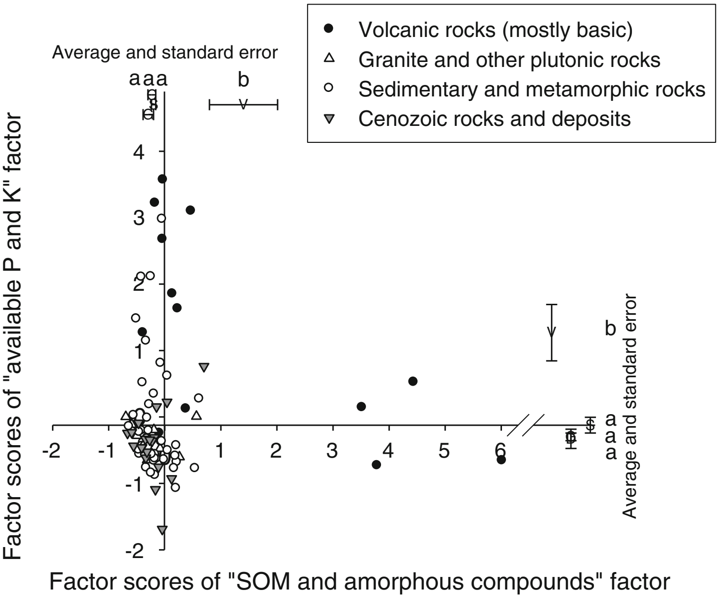


Fig. 4.4 Relationship between the scores of the "SOM and amorphous" and "available P and K" factors

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 in some soils from sedimentary and metamorphic rocks, which are mostly distributed in the western region around Kigoma and the hillslopes near Tanga, and, in contrast, were usually low in soils from granite, except for those of the southern highland.

Figure 4.6 shows the influence of the amount of precipitation on the scores of selected factors. There was no clear relationship between the amount of precipitation and the factor scores of acidity or texture. Although it was expected that a 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 them; this indirectly suggested that the influence of parent materials on soil properties was stronger than that of climatic factors among the soils studied.

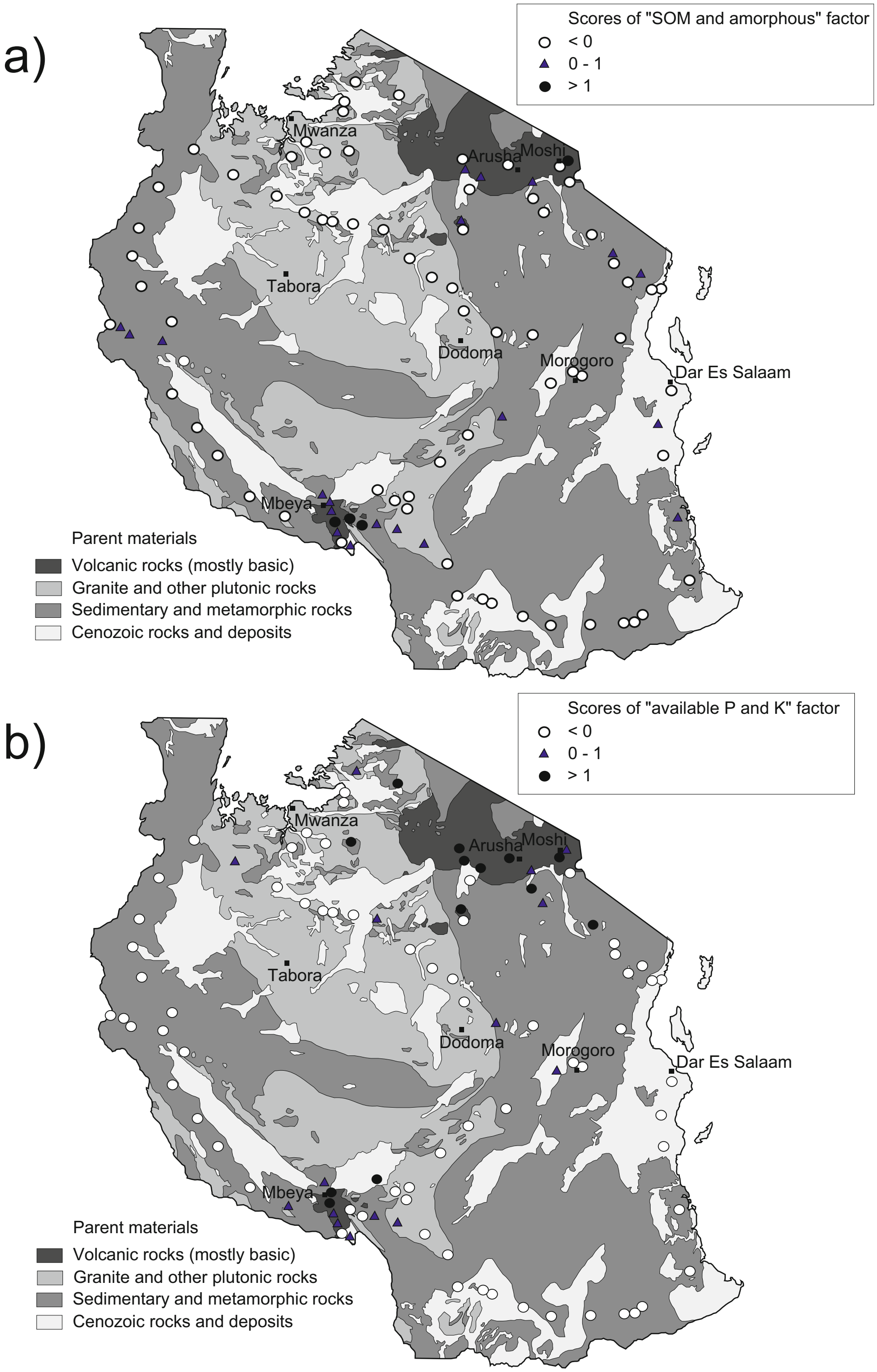


Fig. 4.5 Distribution patterns of scores of (**a**) “SOM and amorphous,” (**b**) “available P and K,” and (**c**) “texture” factors in relation to geological conditions

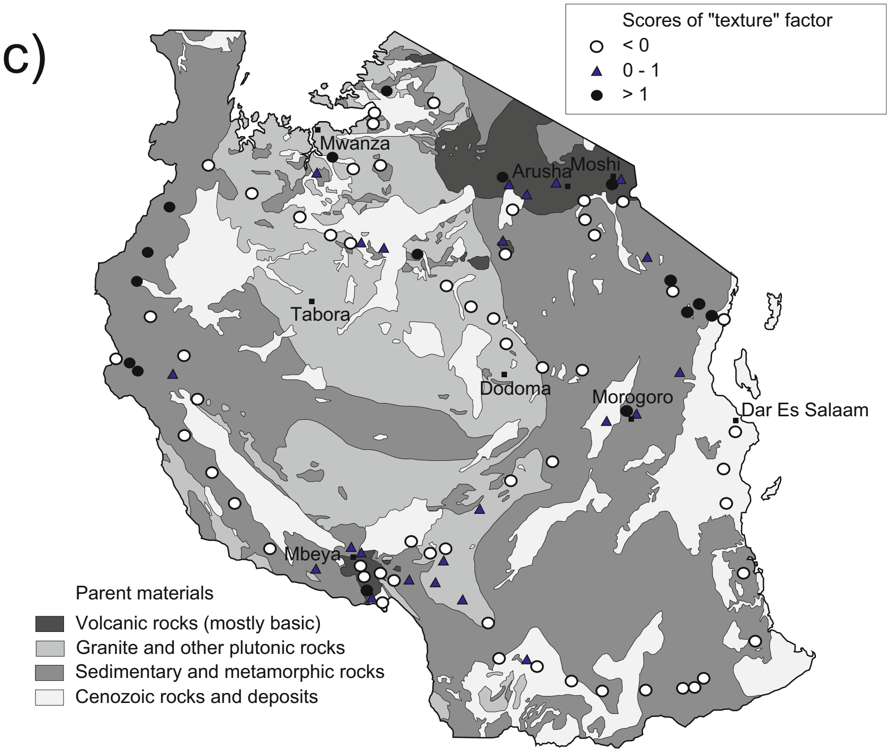


Fig. 4.5 (continued)

4.6 Pedogenetic Conditions Determining the Clay Mineralogy of the Soils

Figure 4.7 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 Fig. 4.8. Stepwise multiple regression indicated that the abundances of 1.4-nm minerals (mostly smectite) could be expressed by the following equation:

$$\begin{aligned} 1.4 - \text{nm minerals}\ (\%) &= 6.38 + 13.4\ (\text{sodicity factor}) \\ &\quad -9.78\ (\text{SOM/amorphous factor}) \\ &\quad +3.17\ (\text{P/K factor}); r^2 = 0.58\ (p < 0.01, n = 90) \end{aligned} \tag{4.1}$$

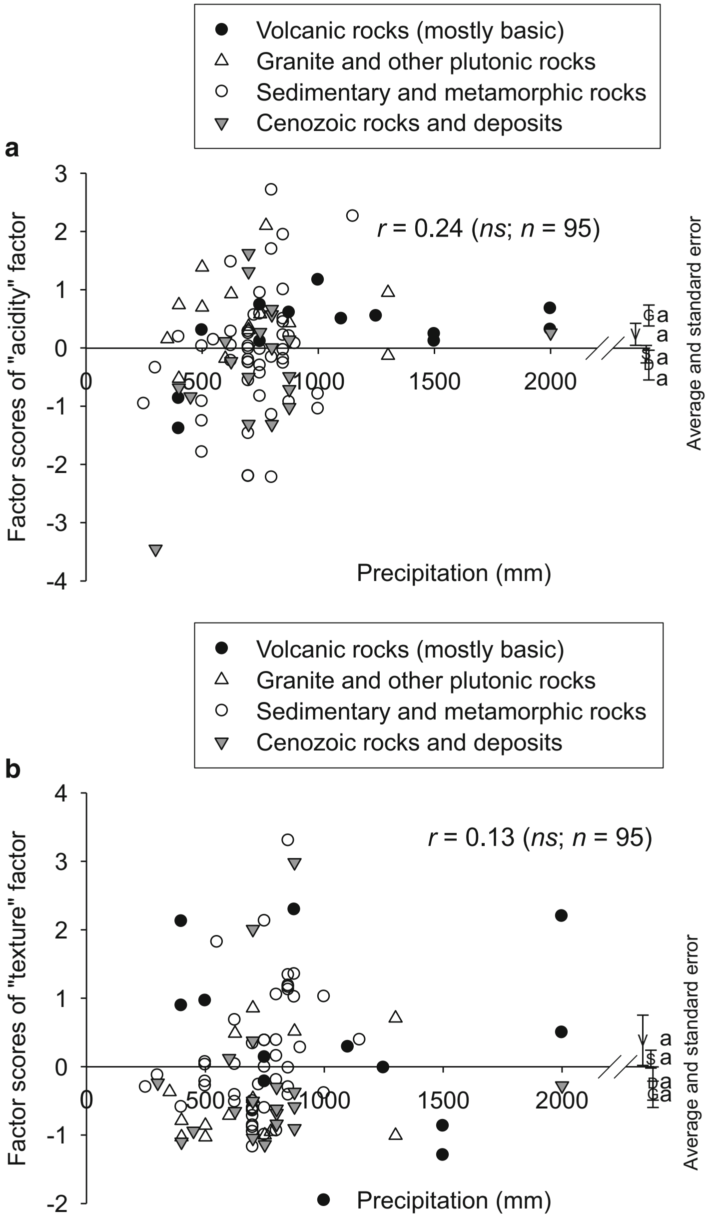


Fig. 4.6 Relationships between precipitation and scores of (**a**) "acidity" and (**b**) "texture" factor

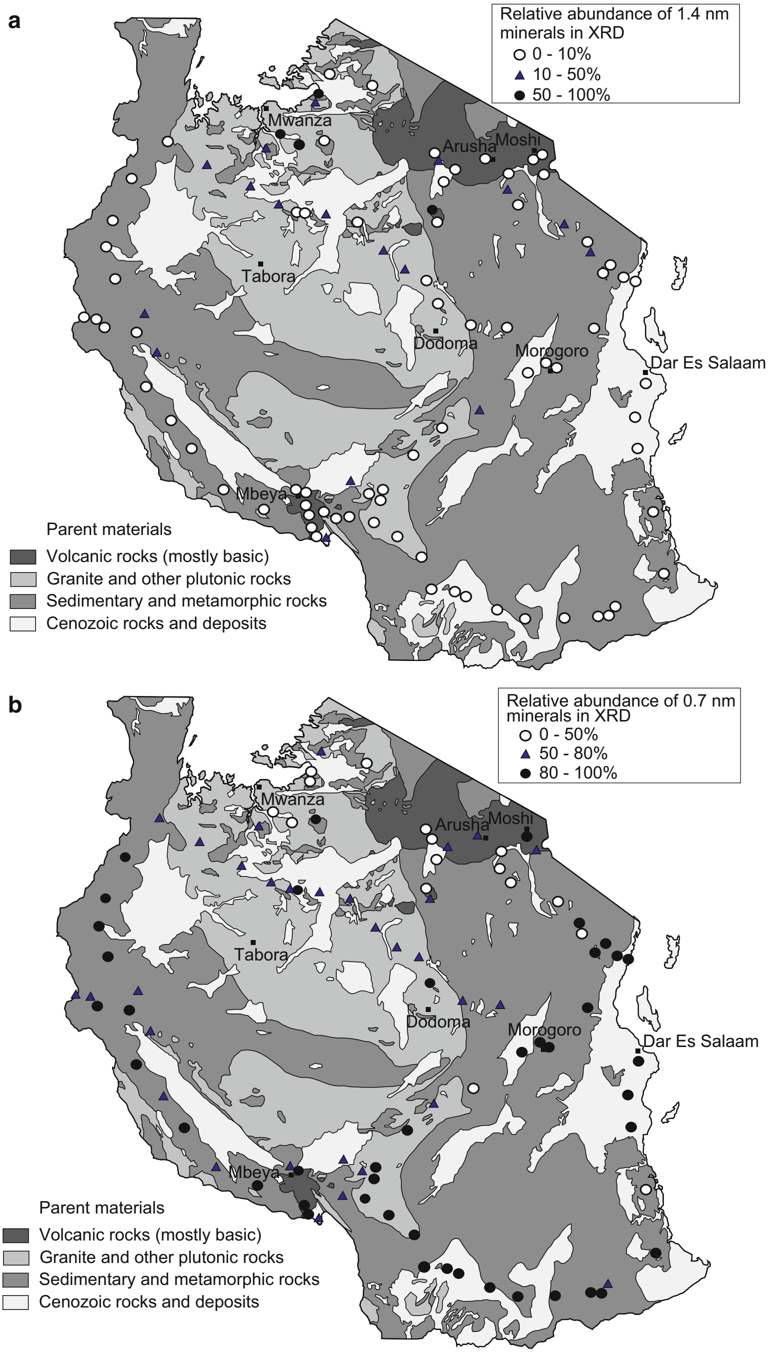


Fig. 4.7 Distribution patterns of clay mineralogy in relation to geological or climatic conditions. Abundances of (**a**) 1.4 nm and (**b**) 0.7 nm minerals

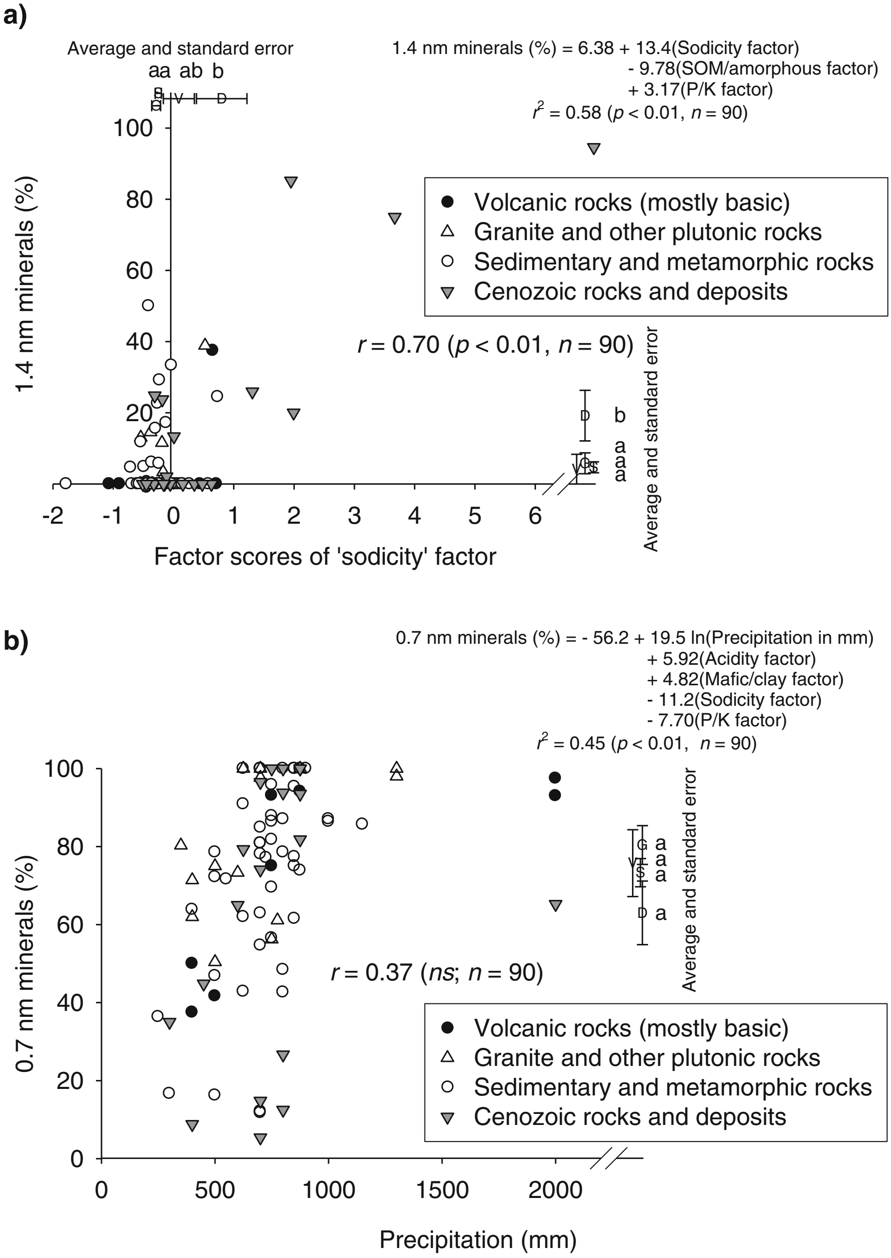


Fig. 4.8 Relationships between clay mineralogy and soil and climatic factors. Abundances of (**a**) 1.4 nm and (**b**) 0.7 nm minerals

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:

$$\begin{aligned} &0.7-\text{nm minerals } (\%) = -56.2 + 19.5\ln\ (\text{precipitation in mm}) \\ &\quad +5.92\ (\text{acidity factor}) + 4.82\ (\text{texture factor}) - 11.2\ (\text{sodicity factor}) \\ &\quad -7.70\ (\text{P/K factor}); \qquad r^2 = 0.45\ (p < 0.01, n = 90) \end{aligned} \tag{4.2}$$

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.

4.7 General Discussion on the Soil Conditions in Tanzania with Specific Reference to Potential Agricultural Development

As stated earlier, soil fertility is considered high in and around the volcanic regions owing to the high SOM-related fertility 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 also contribute to the high nutrient retaining potential of the soils. Both the regions, namely, the volcanic regions and the regions around Lake Victoria, are broadly included in the Great Rift Valley, which is the center of the 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. 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 shortage, while the relatively humid areas have less fertile soil that predominantly contains kaolin minerals; hence, these inherently adverse conditions are not favorable for agricultural production and should be taken into consideration when studying the feasibility of agricultural development in different areas in the future.

4.8 Conclusion

Reflecting the wide variation of climatic conditions and parent materials of soils, soil physicochemical properties varied widely in this study. Clay mineral composition was, however, basically similar to the soils developed under ustic moisture regime in Southeast Asia. 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. From the clay mineralogical composition and the relation between the geological conditions (or parent materials) and the annual precipitation and the scores of the four factors, the following observations were made:

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, presumably due to the intensive agricultural management with fertilizer application.
3. The abundance of 1.4-nm minerals (mostly smectite) can be expressed by the following equation:

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

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:

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

From this equation, it was found that kaolin formation is promoted by highly humid conditions and that it is influenced by the acidity and texture of the soil (or parent materials). Hence, it was inferred 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 conducive to modernized agriculture. The semiarid regions in Tanzania suffer from water shortage, while the relatively humid areas have less fertile soil that predominantly contains kaolin minerals. These conditions are not favorable for agricultural

production and should be taken into consideration when studying the feasibility of agricultural development in different areas in the future.

Acknowledgments This chapter is derived in part from an article published in Soil Fertility Status and Its Determining Factors in Tanzania. By Shinya Funakawa, Hiroshi Yoshida, Tetsuhiro Watanabe, Soh Sugihara, Method Kilasara and Takashi Kosaki, 2012. InTech, available online: http://doi/10.5772/29199.

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