Int. Agrophysics, 2006, 20, 337-344

INTERNATIONAL
Agrophysics
www.ipan.lublin.pl/int-agrophysics

Fractal scaling of soil particles in agricultural landscapes of Nigerian savannas*

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Received March 23, 2006; accepted July 6, 2006

A b s t r a c t. Fractal dimensions, D, for soil profiles in the derived and southern Guinea savanna zones of Nigeria were calculated using particle size distribution data. The D values increased with soil depth because of increasing silt and clay with the depths. Thus, D values were significantly correlated with soil particles; negative correlation with coarse particles and positive correlation with fine particles. In the derived savanna, D values ranged from 2.650 to 3.196 whereas in the southern Guinea savanna they ranged from 2.971 to 3.498. Thus, the soils in the derived savanna conformed more with expected fractal scaling of D < 3 than the soils in the southern Guinea savanna. Nonetheless, the results showed that fractal scaling distinguished the differences in particle size distributions between the two agroecological zones and was, therefore, a sensitive approach for characterization of particle size distribution in the savanna. Fractal scaling also showed the differences between particle size distributions along toposequences.

K e y w o r d s: soil profile, particle size distribution, fractal scaling, savanna

INTRODUCTION

Conventionally, soil particles are classified into sand, silt and clay. However, a more detailed evaluation of soil particles is required for the development of pedotransfer functions and fragmentation models (Tyler and Wheatcraft, 1989; Tietje and Tapkenhinrichs, 1993; Comegna *et al*., 1998; Cornelis *et al*., 2001). Fractal scaling has been used as a fragmentation model to describe particle size distribution and soil behaviour (Tyler and Wheatcraft, 1989; 1992; Rieu and Sposito, 1991a; 1991b; Anderson *et al*., 1998). According to Mandelbrot (1989), the fractal geometry can be defined as the study of geometric shapes that may seem chaotic, but are in fact perfectly orderly. A parameter often used to describe the degree of roughness of objects or their heterogeneous nature is the fractal dimension, D. For soils, Rieu and Sposito (1991a), and Tyler and Wheatcraft (1992) showed that D values should be less than 3. However, these boundary conditions depend on soil texture, as values exceeding 3 have been obtained with the number-based model used for scaling particle size distribution (Tyler and Wheatcraft, 1989; 1992; Millán *et al*., 2003). Such situations can be due to errors introduced in assumptions of particle density and dependence on average sizes of soil particles (Tyler and Wheatcraft, 1992). Salako *et al*. (1999) and Salako (2001) reported that D values of soil aggregates under various cultivation intensities in the derived savanna ranged from 2.29 to 2.89, and were influenced by cultivation, slope position and cropping seasons, depending on aggregate sizes (4-10 and <4 mm).

The application of fractal scaling to soil particle size distribution data gives the advantage of describing an array of data with a single parameter, D (Millán *et al*., 2003). Since soil particle size distribution is basic to soil properties and behaviour, the D values derived from them can also be used to predict soil properties. This study was carried out in two savanna regions of Nigeria, where soils are generally sandy (Kowal and Kassam, 1978; Ker, 1995). Besides, the savanna regions of Nigeria are intensively cultivated for food and cash crops (Ker, 1995), making characterization of soils in this region an important exercise toward sustainable agriculture (Salako *et al*., in press). The particle size distributions of soil profiles for some specific locations in the different savanna regions studied have already been reported (Salako *et al*., 1999; Salako and Tian, 2004). Thus, the present study was carried out to determine the D values of these particle size distributions and the implications for soil properties.

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*This work was supported by a grant from the Swedish International Development Agency (SIDA).

MATERIALS AND METHODS

Site description

Soil samples were collected from profiles or soil surface at Ibadan and Alabata, about 20 km north of Ibadan in southwestern Nigeria, and also in Mokwa, Gadza and Kuchi in northwestern Nigeria (Table 1). The southwestern Nigeria locations are in the derived savanna (DS) while the northwestern Nigeria locations are in the southern Guinea savanna zone (SGS). Along a toposequence, soils vary from Alfisols in the upslope and midslope to Inceptisol and Entisols in the lower slope positions (Moormann *et al*., 1975; Kowal and Kassam, 1978). Geologically, soils in the DS and even parts of the SGS were formed on the basement complex rock while part of the soils in the SGS were formed on Nupe sandstones. At Ibadan, the basement complex parent material is mainly biotite and granite gneiss, whereas it is quartzite at Alabata (Salako *et al*., in press). Both the DS and SGS are intensively cultivated for arable crops such as cereals *eg* maize, rice, sorghum and millet, tuber and root crops *eg* yam and cassava. Cattle rearing and animal husbandry are also common agricultural practices in the savanna regions.

In the DS, the Ibadan landscapes studied were located in the International Institute of Tropical Agriculture (IITA), Ibadan. In IITA, four sites were used for the study but only at

T a b l e 1. Description of locations, soil sampling and land use for the various agricultural landscapes considered in this study

Location	Latitude	Longitude	Soil sampling	Land use
		Derived savanna		
Ibadan (IITA-WBIII)	7.39	3.90	Soil profile (0-200 cm) sampled at every natural horizon and systematically at 15 cm depth increment up to 200 cm along a toposequence	Agroforestry/cover cropping/maize + cassava; natural fallow
Ibadan (IITA-WB14)	7.39	3.90	Surface soil (0-15 cm depth only) along a toposequence	Planted herbaceous legume fallow (*Pueraria phaseoloides*); natural fallow
Ibadan (IITA-D2)	7.39	3.90	Surface soil (0-15 cm depth only) along a toposequence	Planted herbaceous legume fallow (*Pueraria phaseoloides*); natural fallow
Ibadan (IITA-D19)			Surface soil (0-15 cm depth only) along a toposequence	Planted herbaceous legume fallow (*Pueraria phaseoloides*); natural fallow
Alabata, near Ibadan	7.59	3.87	Soil profile (0-200 cm) sampled at every natural horizon along a toposequence	Herbaceous/shrub legume fallows in rotation with maize
		Southern Guinea savanna		
Mokwa	9.28	5.05	Soil profile (0-220 cm) sampled systematically at 15 cm depth increment up to 200 cm, then 30 cm depth increment downward	Agroforestry; researcher-managed farmers' fields, natural fallow
Gadza and Kuchi, near Bida	9.00-9.10	5.98-6.30	Surface soil (0-15 cm depth) along a toposequence	Herbaceous legume fallows; *Pueraria phaseoloides* and *Centrosema brasilianum*

one site was a soil profile sampled (Table 1). Six soil profiles were described at IITA and 8 were described in Alabata. Soil profiles were laterally spaced at between 19 and 48 m apart.

In Mokwa, 9 soil profiles were dug for soil description. The profiles were dug in upper slope portions of the landscapes at two farmer-researcher managed agroforestry plots that were about 5 km apart. In Gadza and Kuchi, near Bida, surface soils were sampled along toposequences of about 200 m in length. Slopes of all the toposequences studied ranged from 2 to 8%.

Soil sampling and laboratory analysis

Soil profiles at IITA-WBII and Alabata in the DS (Table 1) were sampled according to pedologic horizons. In addition, soil profiles at IITA-WBIII were sampled systematically at 15 cm depth increments. At Mokwa in the SGS, soil profiles were only sampled at 15 cm depth increments down to 220 cm depth. For other locations, where soil profiles were not dug in the DS, SGS and NGS, surface soil was sampled at 0-15 cm depth.

Air-dried samples were processed to obtain ≤ 2 mm for the determination of particle size distribution by pipette method (Gee and Bauder, 1986). Oven-dry sand was further sieved into very coarse sand (1-2 mm), coarse sand (0.5-1 mm), medium sand (0.25-0.50 mm), fine sand (0.1-0.25 mm) and very fine sand (0.05-0.10 mm).

Data analysis

Fractal scaling was carried out using the number-based model (Tyler and Wheatcraft, 1992; Kozak *et al*., 1996; Turcotte, 1997; Anderson *et al*., 1998; Salako *et al*., 1999), as follows :

$$N_{>R} = kR^{-D} \quad (1)$$

where: $N_{>R}$ is the cumulative number of particles, R is the radius of particles, k is a proportionality constant and, D is the fractal dimension.

The number of particles was obtained by assuming a particle density, ρ_s, of 2.65 g cm^{-3}. A spherical shape was also assumed for sand and silt, while a cubical shape was assumed for clay. The radius was obtained from the average size of each particle size. For instance, very coarse sand which ranged from 1 to 2 mm had an average size of 1.5 mm and an average radius of 0.75 mm. From these data, the corresponding volume, v, was calculated and used to obtain the mass of a single particle as follows:

$$M = \rho_s v \quad (2)$$

Number of particles in each particle class was obtained by determining the measured size in particle size distribution data with the mass of a single particle, M. Equation (1) was applied as a log-log regression of $N_{>R}$, versus R, to obtain D as the slope and log k as the intercept with corresponding coefficient of determination, r^2.

Equation (1) was adopted for fractal scaling in this study because it leads to the evaluation of fragmentation fractal dimension which on agricultural landscapes can indicate changes caused by different cultivation practices *eg* tillage or cropping strategies (Anderson *et al*., 1998; Salako *et al*., 1999). Equation (1) has further been shown to differentiate between soil textures (Tyler and Wheatcraft, 1992; Turcotte, 1997; Millán *et al*., 2003) which were expected to vary within and between soil profiles in the savanna region due to soil heterogeneity (Moormann *et al*., 1975).

All data were subjected to analysis of variance using SPSS for Windows (SPSS, 1999). Soil horizons or systematically sampled soil depths were compared by treating the horizons or depths as a sequence of soil depth, labelled I, II, III,……n, number of horizons or depth. For instance, if pedon A had topsoil horizon depth of 0-20 cm and pedon B had 0-15 cm topsoil depth on the same toposequence, the average depth range for Horizon I on the slope was 0-18 cm. Pearson correlation coefficients and levels of significance of regression (P values) were calculated.

RESULTS AND DISCUSSION

Fractal scaling of soil particles in the derived savanna

Fine soil materials increased with soil depth in profiles of soils in the derived savanna (Tables 2 and 3). Fractal dimensions at Ibadan ranged from 2.650 to 3.196. At Ibadan, silt + clay at 10-30 cm depth was significantly lower than the content at 98-142 and 142-200 cm depths. Fractal dimension, D, was significantly different between 10-30 and 142-200 cm depths.

At Alabata, the 0-20 cm depth had a lower silt+clay than the 77-127 and 127-200 cm depths (Table 3). Furthermore, the 20-40 cm depth had a significantly less silt+clay than the 40-77, 77-127 and 127-200 cm depths. For D values, the 0-20 cm depth and 20-40 cm depth had significantly lower

T a b l e 2. Clay and silt content and the fractal dimensions of soil particles at Ibadan, SW Nigeria

Soil depth (cm)	Silt + Clay (g kg^{-1})	Fractal D
0-10	209	2.88
10-30	196	2.84
30-58	326	2.85
58-102	388	2.86
102-142	449	2.92
142-200	520	2.97
LSD (P < 0.05)	194	0.124

T a b l e 3. Clay and silt content and the fractal dimensions of soil particles at Alabata, SW Nigeria

Soil depth (cm)	Silt + clay ($g\ kg^{-1}$)	Fractal D
0-20	178	2.86
20-40	210	2.89
40-77	320	2.99
77-125	403	3.06
125-200	365	3.05
LSD ($P < 0.05$)	83	0.060

values than the 40-77, 77-127, and 127-200 cm depths. Also, the 40-77 cm depth had significantly lower D value than the 77-127 and 127-200 cm depths. Fractal dimensions at Alabata ranged from 2.809 to 3.164.

For both Ibadan and Alabata, increasing contents of silt + clay resulted in an increase in D values (Tables 2 and 3; Figs 1 and 2). The outlier (Fig. 1) suggests that quantities of particles alone did not explain the D values, a fact which is reflected by the r^2 of 0.5756. Figures 1 and 2 suggest further that different D values could be obtained with similar quantities of fine materials. These differences highlight the possibility of different fragmentation processes which could result in different shapes of fine particles. This explanation is advanced in view of the fact that soils at Ibadan developed mainly on biotite and granite gneiss parent materials, whereas those at Alabata developed on quartzite. Furthermore, the application of Equation 1 in this study was based on division of sand into different classes, while silt and clay were not so divided. The values of D could be affected by the definition applied for the maximum and minimum linear dimentions, r_{max} and r_{min}, respectively (Anderson *et al.*, 1998). Although fractal dimensions of soil particles are not expected to exceed 3, values exceeding 3 often occur due to assumptions regarding particle density and average sizes of particles (Rieu and Sposito, 1991a; Tyler and Wheatcraft, 1989; 1992; Millán *et al.*, 2003). Tyler and Wheatcraft (1992) stated that instead of the number-based model, the mass-based model could be used to obtain a better fractal scaling of particle size distribution. However, it is expected that for a fractal object, the value of D must exceed its

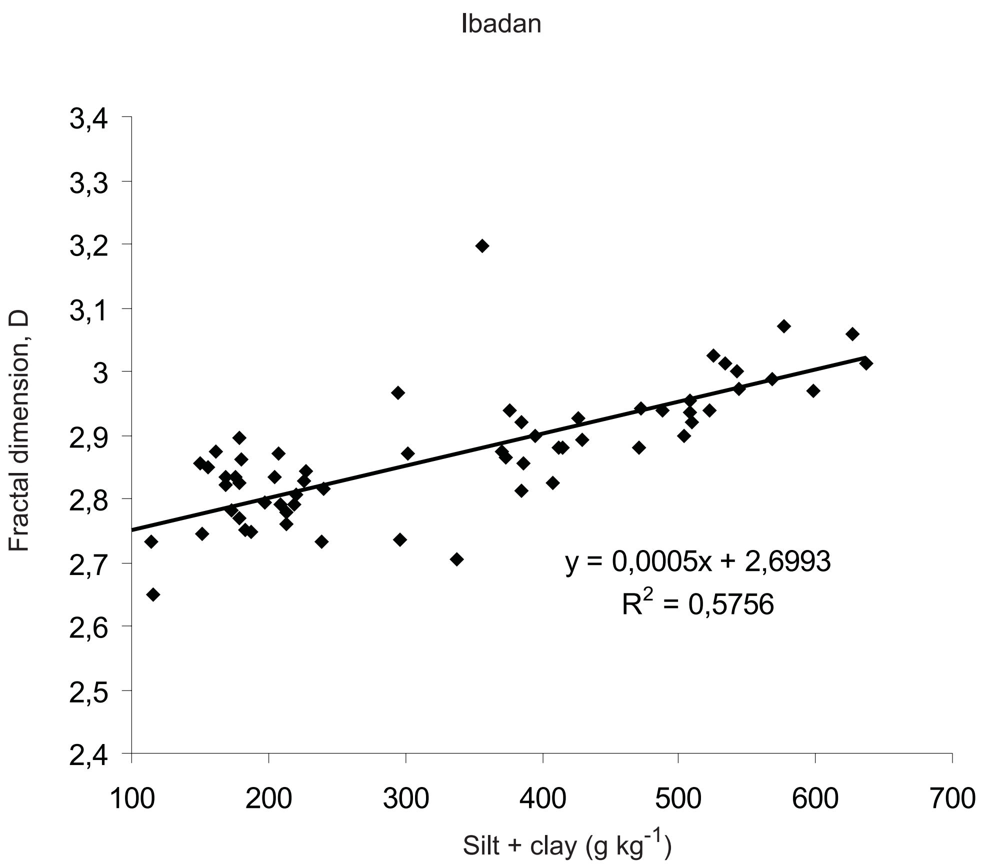

Fig. 1. Relationship between fractal dimension, D and silt+clay content at Ibadan (derived savanna), SW Nigeria.

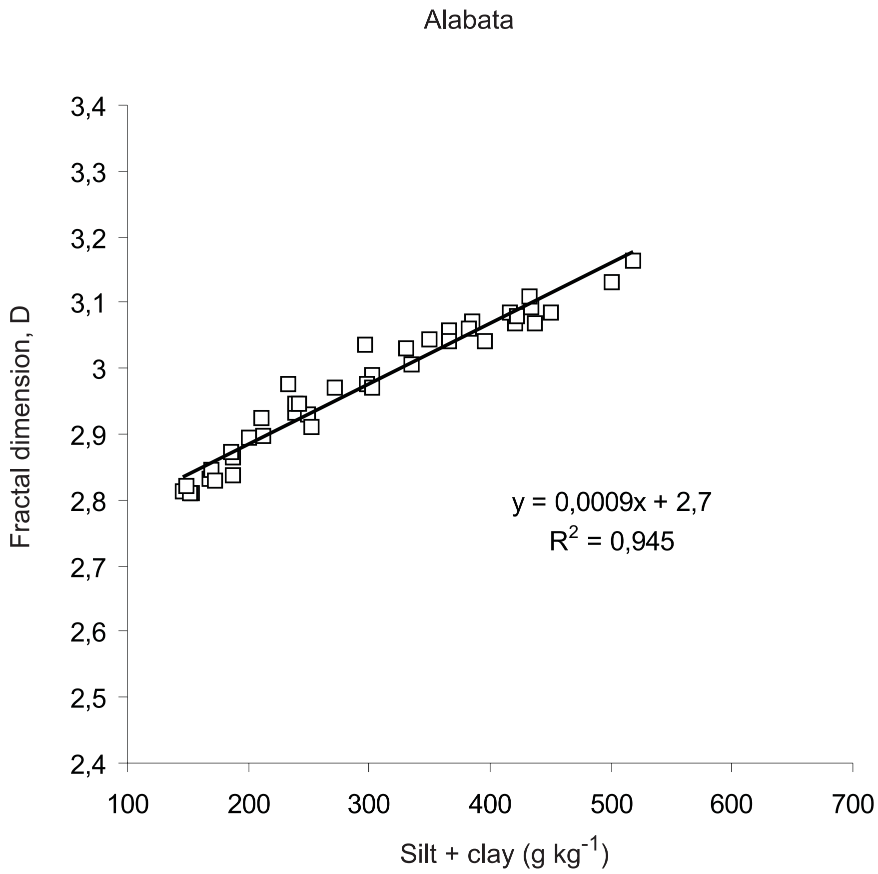

Fig. 2. Relationship between fractal dimension, D and silt + clay content at Alabata (derived savanna), SW Nigeria.

topological dimension (Mandelbrot 1989; Turcotte, 1997). Perfect and Kay (1991) reported D values which ranged from 2.51 to 3.51 for aggregates fragmented by wet-sieving and observed that D increases with increasing fragmentation. Thus, values exceeding 3 probably indicated an expression of a more cubical shape of soil particles than others with less than 3 and were more associated with high content of very fine materials in the soil. Within the derived savanna, fractal scaling was more applicable at Alabata than Ibadan.

Fractal scaling of soil particles in the southern Guinea savanna zone

The shapes of the curves describing variations of D with soil depth, and silt + clay with soil depth, are similar for Mokwa (Fig. 3) suggesting that the strong correlation between D and silt + clay observed in the derived savanna (Figs 1 and 2) also applied here. However, D values of the soil profile generally exceeded 3 (2.971-3.498) in the southern Guinea savanna. This was due to a higher content of silt + clay in the southern Guinean savanna compared with the derived savanna. The curves in Fig. 3 suggest that the fragmentation processes of the upper and lower layers of soil relative to the 40-100 cm soil depth (where bulges occurred in the 2 curves) were different. Thus, the 0-40, 40-100 and 100-220 cm depths were layers with distinct physical properties. In spite of the argument that D values for soil particles should not exceed 3 (Tyler and Wheatcraft, 1992), the differences in D values of the DS and SGS profiles showed that fractal scaling was very sensitive to differences in soil particle size distributions between the two zones and, therefore, useful in soil characterization.

Figures 1-3 show that there were differences in the fragmentation processes on the agricultural landscapes, which could be due to differences in parent materials, hence weathering processes. Therefore, the D values distinguished the agricultural landscapes in spite of the fact that some D values exceeded 3. Although the heterogeneity in soil particle properties was highlighted with increasing silt+clay contents, Figs 1-3 suggest that other particle properties such as different shapes of particles which could arise in the process of accretion or fragmentation (Perfect and Kay, 1995) would further accentuate this heterogeneity. This is

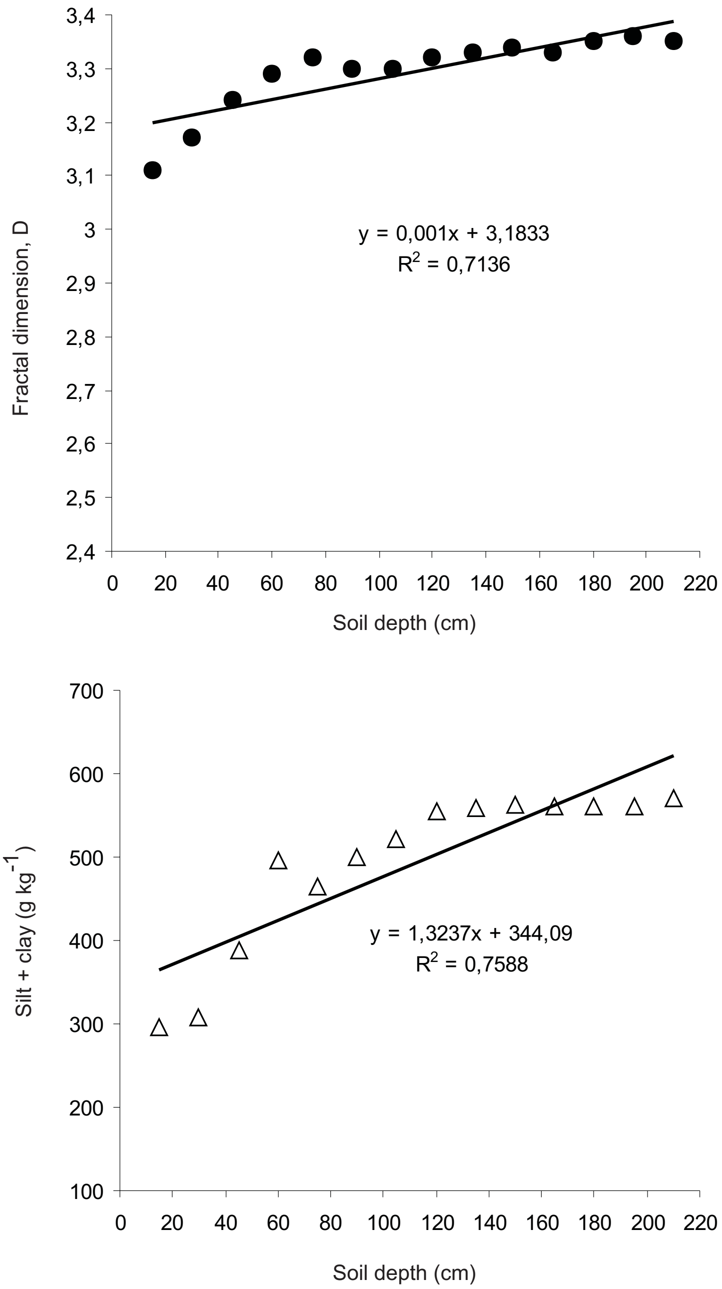

Fig. 3. Relationship between fractal dimension, D, silt + clay content and soil depth at Mokwa (southern Guinea savanna), NW Nigeria.

why similar silt+clay contents could result in different D values. Based on this deduction, it can be deduced that soil pores would be tourtuous or heterogeneous in the following order: Mokwa (SGS) > Ibadan (DS) > Alabata (DS). Kozak *et al*. (1996) stated that models more sophisticated than scale-invariant fragmentation models are required to simulate particle size distribution. Multifractal scaling has been suggested in this respect (Turcotte, 1997; Anderson *et al*., 1998; Millán *et al*., 2003).

Effect of slope position on surface soil fractal dimensions

At both the derived and the southern Guinea savanna zones, D values were higher at the upper slope than at the middle and lower slopes (Table 4). This was due to the fact that colluvial materials on the topsoil in the middle and lower slope were coarser than the topsoil particles in the upper slope. This is a plausible argument because sand and

T a b l e 4. Comparison of surface soil (0-15 cm depth) particle size distribution along toposequences in the derived and southern Guinea savanna

Slope position	Particle size distribution (g kg^{-1})			Fractal D
	Total sand	Silt	Clay	
	IITA-Ibadan (WB14, D2, D19) in the derived savanna			
Lower	784	139	78	2.72
Middle	761	153	86	2.75
Upper LSD	729	113	158	2.80
($P < 0.05$)	55	NS	NS	0.024
	Gadza and Kuchi, southern Guinea savanna			
Lower	855	113	33	2.72
Middle	857	102	41	2.76
Upper LSD	847	106	47	2.78
($P < 0.05$)	10	11	6	0.026

gravel contents had negative correlations (r values from -0.61 to -0.97) with D, while silt and clay content had positive correlations (Figs 1-3). The results also suggest that soil differences along toposequences can be expressed for the savanna landscapes using fractal scaling.

CONCLUSIONS

1. The D values for the derived savanna was between 2.650 and 3.196, whereas they ranged from 2.934 to 3.498 in the southern Guinea savanna soil profiles.

2. This was a reflection of higher silt + clay content in the southern Guinea savanna soil profiles than in the derived savanna soil profiles.

3. The results also showed a better conformity of the derived savanna soil with fractal scaling than the southern Guinea savanna soils. Even within the derived savanna, there were differences in the conformity of particle size distributions with fractal scaling due to spatial variability. Fractal scaling was, therefore, a sensitive approach to understanding the nature of soils in the savanna regions of Nigeria.

4. The D values increased with soil depth because of increasing silt + clay content. Furthermore, differences in soil particle size distribution along toposequences were indicated by the D values for both the derived and southern Guinean savanna.

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