APPLICATION OF FRACTAL THEORY IN QUANTIFYING SOIL AGGREGATE STABILITY AS INFLUENCED BY VARYING TILLAGE PRACTICES AND COVER CROPS IN NORTHERN GUINEA SAVANNA, NIGERIA †

[APLICACIÓN DE LA TEORÍA FRACTAL EN LA CUANTIFICACIÓN DE LA ESTABILIDAD AGREGADA DEL SUELO INFLUENCIADA POR DIVERSAS PRÁCTICAS DE LABRANZA Y CULTIVOS DE CUBERTURA EN LA SABANA NORTE DE GUINEA, NIGERIA]

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SUMMARY

Background. Soil aggregate stability varies with management practices like tillage and soil organic matter management. **Objective.** The objectives of this study were to (i) Explore a fractal theory to investigate the extent of soil fragmentation in soil of Samaru, Northern Nigeria, subjected to different tillage practices and covers crops for the purpose of improving soil aggregate stability (ii) Establish a relationship between fractal dimension (D) and mean weight diameter (MWD). **Methodology.** A three years field trials was conducted with three tillage practices (no-till, reduced till and conventional till) as main treatments and four cover crops (*Centrosema pascuorum, Macrotyloma uniflorum, Cucurbita maxima* and *Glyine max*), and a bare/control (no cover crop) as sub treatments. The trial was laid out in randomized complete block design, split plot arrangement and replicated three times. Soil samples were collected at 0-15 cm prior to trial establishment for routine soil physical and chemical properties and at depths 0-5, 5-10, 10-15 and 15-20 cm at the end of each cropping season each year for soil aggregate stability test. **Results.** No-till soils had 12.58% better soil aggregate stability than soils under reduced and conventional tillage systems. Also, no-till soils had 2.40 % less fragmented soil aggregates than Reduced and Conventional till soil as indicated by the fractal dimension of soil aggregates. Soils under *Macrotyloma uniflorum* cover crop, were on the average 2.33% less fragmented than soils under *Centrosema pascuorum, Glycine max* and *Cucurbita maxima* but 4.56% less fragmented than soils with no cover crops. **Implication,** No-till and reduced till systems; and cover cropping better enhanced soil aggregate stability due to better accumulation of organic matter emanating from crop residues return to soil in these practices. **Conclusion.** Conservation tillage and the use of cover crops lowered soil aggregate fragmentation relative to conventionally tilled system and bare soil with no cover crop. The strong linear relationship established between MWD and fractal dimension showed over 80% dependency, suggesting that fractal dimension is another useful index for evaluating soil aggregate stability.
Key words: Fractal dimension; Mean weight diameter; soil aggregate stability; tillage; cover crop.

RESUMEN

Antecedentes. La estabilidad de los agregados del suelo varía con las prácticas de manejo como la labranza y el manejo de la materia orgánica del suelo. **Objetivo.** (i) Explorar una teoría fractal para investigar el grado de fragmentación del suelo en el suelo de Samaru, en el norte de Nigeria, sometido a diferentes prácticas de labranza y cultivos de cobertura con el fin de mejorar la estabilidad de los agregados del suelo (ii) Establecer una relación entre la dimensión fractal (D) y el diámetro de peso medio (MWD). **Metodología.** Se realizó un ensayo de campo de tres años con tres prácticas de labranza (siembra directa, labranza reducida y labranza convencional) como tratamientos principales y cuatro cultivos de cobertura (*Centrosema pascuorum, Macrotyloma uniflorum, Cucurbita maxima* y *Glyine max*), y un testigo desnudo (no cultivo de cobertura) como subtratamientos. El ensayo se presentó en un diseño de bloques completos al azar, en un arreglo de parcelas divididas y se repitió tres veces. Se recolectaron muestras de suelo a 0-15 cm antes del establecimiento de la prueba para determinar las propiedades físicas y químicas del suelo de rutina y a profundidades de 0-5, 5-10, 10-15 y 15-20 cm al final de cada temporada de cultivo cada año para el suelo. prueba de estabilidad agregada. **Resultados**. Los suelos de labranza cero tuvieron un 12.58% más de estabilidad de los agregados del suelo que los suelos bajo sistemas de labranza reducida y convencional. Además, los suelos de

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labranza cero tenían 2.40% menos de agregados de suelo fragmentados que los suelos de labranza reducida y convencional, como lo indica la dimensión fractal de los agregados del suelo. Los suelos bajo el cultivo de cobertura de *Macrotyloma uniflorum* estaban en promedio 2.33% menos fragmentados que los suelos de *Centrosema pascuorum*, *Glycine max* y *Cucurbita maxima*, pero 4.56% menos fragmentados que los suelos sin cultivos de cobertura. **Implicaciones.** Sistemas de labranza cero y labranza reducida; y cultivos de cobertura mejoran la estabilidad de los agregados del suelo debido a una mejor acumulación de materia orgánica que se origina de los residuos de cultivos que regresan al suelo en estas prácticas. **Conclusión.** La labranza de conservación y el uso de cultivos de cobertura redujeron la fragmentación de los agregados del suelo en relación con el sistema de labranza convencional y el suelo desnudo sin cultivo de cobertura. La fuerte relación lineal establecida entre MWD y la dimensión fractal mostró una dependencia superior al 80%, lo que sugiere que la dimensión fractal es otro índice útil para evaluar la estabilidad de los agregados del suelo.
Palabras clave: Dimensión fractal; Diámetro ponderal medio; estabilidad de los agregados del suelo; labranza; cultivo de cobertura.

INTRODUCTION

The ability of cohesive forces between soil particles to withstand applied disruptive forces (external stress) simulating the phenomena that occurs on field is known as aggregate stability. Good soil aggregate stability induces good soil structure, soil structure influences seed germination, plant root growth, and water and contaminants transport. However, soil tillage and management practice greatly modify soil structure and consequently soil aggregate stability (Pirmoradian *et al*., 2005). Blanco-Canqui and Lal (2004) indicated that soil aggregation is an important factor controlling plant growth and carbon sequestration, as well as nutrient flow (Tripathi *et al*., 2008). It is therefore necessary to implore a scale to quantify strength of stability of soil aggregate.

Aggregate size distribution had been used exhaustively to quantify soil aggregate stability; however, it is necessary to use a single parameter to characterize soil aggregate size distribution. As a result, several empirical indices have been proposed for describing the entire distribution with a single value. Van Bavel (1949) used mean-weight diameter (MWD) to integrate aggregate size distribution obtained by mechanical sieving. Mazurak (1950); suggested that the geometric mean diameter (GMD) may be more appropriate. However, Baldock and Kay (1987) used the following power function to describe the cumulative percentage of aggregates by weight less than a characteristic linear dimension x (e.g., equivalent diameter or height);

$$W<x = A(x)^{B}$$

Where: W is the cumulative percentage weight of aggregate; x is the characteristic linear dimension; and A and B are regression constants. Since the coefficient B exhibited maximum variation, it was used as the index of aggregate size distribution.

Previous indices to quantify soil structure, often, were empirical. Recent advances in fractal theory introduced scaling parameters, as fractal dimension that may be suitable for characterizing aggregate-size distribution in soil. Several researchers explored this possibility (Perfect and Kay, 1991; Young and Crawford, 1991; Rieu and Sposito, 1991a, b; Perfect *et al*., 1992, 1994; Rasiah *et al*., 1992 and Anderson *et al*., 1997).

According to Mandelbrot (1982), fractals are characterized by a power-law relation between the number and size of objects. The value of fractal dimension (D) is equal to the absolute value of the exponent in the relation

$$N_{>}x = k(x)^{-D}$$

Where N >x is the cumulative number of objects greater than x, and k is a constant corresponding to the number of fragments of unit length. The value of D depends on the shape of individual objects within the distribution, and the overall extent of aggregate fragmentation. The larger the value of D, the greater the aggregate fragmentation; this means that the shape of aggregate may be similar in various ranges of aggregate size. However, it may be assumed that the value of D is scale invariant in shape.

A parameter which has been primarily estimated from the wet-sieving data is the fractal dimension (D). It is found from the regression of logarithms of mass (mass-based approach) or cumulative number (number-based approach) of stable aggregates to the logarithms of characteristic linear dimensions (such as radius or length). The fractal dimension is derived as the absolute value of the exponent in the relationship (Perfect and Kay, 1991). A review by Anderson *et al*. (1998) stated that the power-law distribution observed in the fragmentation of natural materials as a result of scale invariance of the fragmentation mechanism implies that the zones of weakness that are predisposed to failure exist at all scales.

According to the fractal fragmentation model of Turcotte (1986), the fractal dimension in soil is expected to be less than 3 since the inequality D ≥3 would require that the probability of grain fragmentation be ≥1 which is not valid. Perfect and Kay (1991), however, indicated that the value of D determined from aggregate-size distribution is a measure of soil fragmentation and showed that it can be as high as 3.5.

Fractal dimension has been used to characterize the influence of soil properties and cropping systems on the size distribution of aggregate, subsequent to fragmentation (Rasiah *et al*., 1992, 1993), these investigators have reported values of D>3. McBratney (1993) has also questioned the merit of values D>3 and their physical significance.

Perfect *et al.* (1993) showed, however, that values of D>3 are theoretically possible if the fragmentation process exhibits multi fractal behavior. Physically, values of D>3 mean that fragments are retained at each level in the hierarchy than is possible for fractal fragmentation. Rasiah and Biederbeck (1995) have shown that values of D obtained using the non-linear fitting procedure in general were smaller and more accurate than those obtained using the linear procedure. Perfect *et al*., (1994) reported a range of 1.179 to 2.803 for values of D estimated for fragmented aggregates. Several authors (Young and Crawford, 1991; Tyler and Wheatcraft, 1992; Crawford and Matsui, 1996 and Kozak *et al.*, 1996) have observed that the approach for estimating D values influences the results obtained. Rasiah *et al.* (1992) and Perfect *et al*., (1994) reported that the estimates of D from aggregate size distribution data varied with cropping, wetting and tillage treatments. Perfect and Kay (1991) noted that the value of D was a measure of fragmentation and irregularity, which increases with increasing input and time under corn production. Furthermore, Anderson *et al*. (1998) observed that the main factor that limits the estimation of fragmentation fractal dimension is that estimates are made from a distribution of aggregates or particles, which bear no resemblance to the original soil matrix.

Perfect and Blevins (1997) have shown that fractal parameters are sensitive to tillage treatment. Mould-board ploughing increases soil aggregate fragmentation in comparison with no-till. Sepaskhah *et al.* (2000) compared indirect number-size fractal dimension (Dn), mass-size fractal dimension (Dm) and mean-weight diameter (MWD) as measures of soil aggregate stability. The fractal dimensions Dn and Dm decreased with increasing amount of mulch application indicating an increase in aggregate stability as a result of the addition of the mulch. Salako *et al*. (1999) evaluated soil macro aggregate stability under different fallow management systems and cropping intensities in southwestern Nigeria; they reported higher D values (more fragmentation) in cultivated soils relative to fallowed soil where aggregates stability was enhanced. In addition, Salako *et al.* (1999) reported that *pueraria* system favoured better soil aggregate stability than the bush fallow and *leucaena* systems under continuous cropping. However, there is a need to implore fractal dimension, to test macro aggregate stability of low organic matter soil of Northern Nigeria, under different management practices. The objectives of this study are to: (i) use fractal theory to evaluate the extent of soil fragmentation in soil of Samaru, Northern Nigeria, subjected to different tillage practices and covers crops for the purpose of improving soil aggregate stability. (ii) Establish a relationship between fractal dimension and mean weight diameter.

MATERIAL AND METHODS

Description of Study Area

The trials were conducted at the Institute for Agricultural Research (IAR) farm (latitude 11.17358°N, longitude 7.63020°E and altitude of 691 m above sea level) Samaru, Zaria, Northern Guinea Savanna ecological zone of Nigeria. The study area has a long-term mean annual rainfall of 1101±16.1mm (Oluwasemire and Alabi, 2004), with a uni-modal rainfall pattern annually, beginning in April and ending in October. The minimum and maximum mean annual temperature being 18°C and 31.5°C respectively. The soil type is Typic haplustults derived from pre-Cambrian crystalline basement complex rocks with some quaternary aeolian deposits.

Experimental Layout and Soil Sampling

The experimental field was laid out in a randomized complete block design, split plot arrangement and replicated three times. The main treatments were three tillage practices namely: conventional tillage, CT, (ploughing, harrowing and ridging; with crop residue removed at the end of each cropping season as practiced by the local farmers in Northern Nigeria), reduced tillage, RT, (harrow once and crop residue incorporated) and no-till, NT, (no soil disturbance except for seed sowing, and crop residue were left on soil surface), while a control i.e. bare, except for sole maize (no cover crops) and four cover crops namely: *Glycine max, Centrosema pascuorum, Macrotyloma uniflorum* and *Cucurbita maxima*, were the sub treatments. The experimental field was grown to Maize (*Zea mays*) as the test crop for three rainy seasons (2011-2013).

Prior to trial establishment, disturbed and undisturbed soil samples were taken from the experimental field at 0-15 cm depth, for routine soil physical and chemical analyses. After trial establishment, in each year, disturbed auger soil samples were collected in each treatment plot at depths 0-5, 5-10, 10-15 and 15-20 cm. At each sampling depth, in each replication, soil samples were taken at five different spots per plot then bulked as one.

Laboratory analysis

Soil physical and chemical analysis

Disturbed soil samples taken at 0-15 cm depth, were air-dried and sieved through 2 mm mesh, for determination of particle size distibution (Gee and Or, 2002), organic carbon (Nelson and Sommers, 1982), pH (Mcleans, 1982), Total nitrogen (Bremner and Mulvaney, 1982) Available P by Bray No. 1 acid fluoride method and exchangeable bases (Rhodes, 1982). The undisturbed soil sample was used for determination of bulk density by core method (Grossman and Reinsch, 2002).

Macroaggregate stability and distribution

Macroaggregate stability was determined by wet sieving as described by Kemper and Rosenau (1986) and Angers and Mehuys (1993) with slight modification. Twenty grams of 5-10 mm sieved soil sample was placed on 5 mm mesh openings and immersed in water for 5 minutes. After which, it was sieved for 5 minutes using 5 mm, 2 mm, 1 mm, 0.25 mm and 0.125mm mesh openings. The fractionated aggregates were corrected for sand and stones; and MWD was determined as described below.

The proportional weight of sand free aggregates is given as:

$$(\text{Weight of aggregate fraction} - \%\ \text{sand content in the aggregate fraction}) / (\text{Weight of bulk soil} - \%\ \text{sand content in the bulk soil})$$ (Masri and Ryan, 2006)

$$\text{MWD} = \sum_{i=1}^{n} xi\ wi$$

Where xi = mean diameter of two successive sieves
Wi = proportional weight of sand free aggregates

Fractal approach to soil aggregate stability

The cumulative number approach was used to analyze cohesiveness and stability of soil aggregates (Perfect and Kay, 1991; Rasiah *et al*., 1992; Salako *et al*., 1999). The wet sieving data obtained during the macro aggregate stability was used to estimate fractal dimension. Briefly the mass of ten pieces of the air dried 5-10 mm aggregates sizes were taken. Then the volume was measured by the displacement method, where the aggregates were coated with paraffin wax and then immersed in water. The density of aggregates is thus given as the proportion of the mass of soil aggregates to its volume. The volume of each fragmented aggregate was calculated as described by Perfect and Kay (1991) and Salako *et al.* (1999) using the mean size obtained on successive sieves with the assumption that each soil aggregate was a cube. The aggregate density was multiplied by the cubical volume to give the mass of a single aggregate in the total mass of fragments retained on the sieve. The number of aggregates retained on each sieve was then obtained by dividing the total mass of aggregates on each successive sieve by the mass of a single aggregate.

The fractal dimension (D**)** of soil aggregates was obtained by the relationship:

$$N_{>x} = kx^{-D}$$

Where: $N_{>x}$ = Cumulative number of aggregates, X = Mean sieve size (obtained by finding the average value of successive sieve sizes), D = Fractal dimension, k = intercept obtained from the log–log regression analysis

Microaggregates within stable macro aggregates

Microaggregates occluded in stable macroaggregate (>0.25 mm) was determined as described by Six *et al.* (2000) but without using the micro aggregates isolator. A sub sample of 15g oven dried macro aggregates obtained during the wet sieving was slaked in deionized water for 20 minutes to break down large macroaggregates, by placing it on a 0.25 mm sieve and shake it with some glass beads on a reciprocal shaker at low speed (150 rpm) for 5 minutes. The content that passed through the 0.25 mm sieve was passed through a 0.053 mm sieve at a rate of 50 strokes in 2 minutes to ensure that the isolated micro aggregates were water stable (Elliot, 1986). After breaking up the macroaggregates, sand and coarse particulate organic matter were retained on the 0.25 mm screen. All fractions were washed in aluminum pans and oven dried at 60ºC to a constant weight. The difference between the initial weight of macroaggregate and weight of sand and coarse particulate organic matter was adopted as the weight of microaggregates occluded in stable macroaggregate. Hence, proportional weight of microaggregates occluded in stable macroaggregate is given as:

$$\frac{\text{Weight of occluded microaggregate fraction}}{\text{Weight macroaggregate}}$$

Data Analysis

Data collected for the three years of study were subjected to statistical analysis of variance for randomized complete block design, using the generalized linear model (GLM) procedure of statistical analytical software, SAS package (SAS, 2008) Significant difference among treatment means were separated using the Duncan multiple range test.The averages for the three years of study are presented for each parameter evaluated.

RESULTS

Characterization of Soil of the Study Area

The physical and chemical properties of soil of the study area prior to trial establishment is presented in Table 1. The soil is generally loam (L) in texture with 43% sand, 43% silt and 14% clay and moderately acidic in soil reaction, with moderate organic carbon (10.17 g kg^{-1}) and bulk density (1.4 Mg m^{-3}); but poor in total nitrogen (0.72 g kg^{-1}). The soil has very low available phosphorus (2.56 mg kg^{-1}), exchangeable calcium and cation exchange capacity. While exchangeable magnesium, potassium and Sodium are generally low, in line with published findings of savanna soils in Nigeria (Jones and Wild, 1975).

Tillage, cover crop and sampling depth effects on distribution of water stable soil aggregates

Table 2 reveals the effect of tillage, cover crop and soil sampling depth on distribution of water stable soil aggregates at Samaru. Variations due to tillage practices showed that no-till significantly enhanced macroaggregates fractions (10-5, 5-2 and 2-1 mm) relative to RT and CT practices except in 10-5mm soil fraction were NT and RT had statistically similar soil proportional weight. Whereas, the CT practice had significantly higher microaggregates (≤0.25mm) fraction relative to NT soil.

Effect due to cover crops revealed that 10-5mm macroaggregate fraction was not significantly influenced by cover crop. However, *Cucurbita maxima* alongside all other cover crops significantly enhanced soil macroaggregate fractions 5-2, 2-1 and 1-0.25 mm relative to soil with no cover crop. The least microaggregate fraction 0.25-0.125 was observed in soil under *Cucurbita maxima* while soil aggregate fraction <0.125 mm was not significantly influenced by cover crops. The stability of macro aggregate fractions 10-5 and 5-2 mm decreased significantly with increasing sampling depth. While, macro aggregate fractions 2-1 and 1-0.25 mm were significantly least stable at depth 15-20 cm relative to other sampling depths. Conversely, 0.25-0125 and <0.125 mm microaggregate fractions were significantly more stable in soils sampled from depth 15-20 cm relative to all other soil sampling depths.

Effect of tillage, cover crops and sampling depth on soil macro aggregate Stability

The effect of tillage and cover crops on soil macro aggregate stability; as characterized by mean weight diameter (MWD) and fractal dimension (D) is presented in Table 3. Generally, soils under no-till practices had significantly higher soil aggregate stability relative to soils harrowed (reduced tillage) and those harrowed, ploughed and ridged (conventional tillage). No-till soils were 12.58% better than soils under the RT and CT systems with respect to mean weight diameter and they were 2.40 % less fragmented than RT and CT soil as indicated by the fractal dimension of soil aggregates (D). Conversely, the intercept (log k) was significantly higher at the CT soils compared to the RT and no-till.

Variation among soil cover crops did not significantly influence MWD and log k. However, the effect of cover crops on fractal dimension of soil aggregates showed that soils grown to *Macrotyloma uniflorum* as cover crops were the least fragmented; next to it were soils grown to *Centrosema pascuorum*, *Glycine max* and *Cucurbita maxima* while soils with no cover crops were the most significantly fragmented. Soils under *Macrotyloma uniflorum* were on the average 2.33% less fragmented than *Centrosema pascuorum*, *Glycine max* and *Cucurbita maxima* and 4.56% less fragmented than soils with no cover crops

Mean weight diameter, log k and fractal dimension of soil aggregates were significantly influenced by soil sampling depth (Table 3) both MWD and log k decreased with increase in soil depth while D which indicates soil fragmentation increased with increase in soil sampling depth. All the coefficient of determination (r^2) values obtained in the regression graphs of log x (mean sieve sizes) versus log N (number of aggregates retained on each sieve) presented dependencies of 94 to 96 % (Table 3).

Variation due to tillage showed that microaggregate occluded in stable macroaggregate (MiAOSMA) were significantly higher in conservation tillage (NT and RT) practices relative to the conventional tillage practices. Effect due to cover crops showed soil covered with *Glycine max.* had significantly higher microaggregate occluded in stable macro aggregate than all other cover crop plots and the control except for soils under *Cucurbita maxima* that had statistically similar MiAOSMA as soils under *Glycine max*. The subsurface soils (0-15 and 15-20 cm) were significantly higher in MiAOSMA than the surface soils at depth 0-5 and 5-10 cm. However, the surface soil had significantly, the least MiAOSMA

Table 1. Physical and chemical properties at soil depth of 0-15cm of the experimental site prior to trial establishment.

Parameters	Values	% CV
Sand (g kg^{-1})	431.11	5.93
Silt (g kg^{-1})	425.77	6.89
Clay (g kg^{-1})	143.11	14.09
Texture	Loam	-
pH (water)	6.3	1.56
pH ($CaCl_2$)	5.4	2.55
Organic carbon (g kg^{-1})	10.17	20.32
Total nitrogen (g kg^{-1})	0.72	19.41
Available P (mg kg^{-1})	2.56	24.33
Exchangeable Calcium (cmol kg^{-1})	1.96	32.05
Exchangeable Magnesium (cmol kg^{-1})	1.03	33.25
Exchangeable Potassium (cmol kg^{-1})	0.24	37.30
Exchangeable Sodium (cmol kg^{-1})	0.1	51.47
Cation exchange capacity (cmol kg^{-1})	4.3	22.34
Bulk density (Mg m^{-3})	1.47	7.68

CV = coefficient of variability.

Relationship between mean weight diameter and fractal dimension

Figure 1 shows the regression graph of MWD VS fractal dimension, this relationship was described by a linear equation, with an r squared value of 0.832. This relationship suggests over 80% dependency of fractal dimension on mean weight diameter. The data in the plot area showed that as mean weight diameter increases fractal dimension decreases, reason being that mean weight diameter measures the degree of aggregation or cohesiveness of soil while fractal dimension on the other hand measures the extent of fragmentation of soil aggregate.

DISCUSSION

The higher stability of macroaggregate in the no-till soils could be explained in the context of field operation. The no-till plots which had remained undisturbed (untilled) throughout the experimental years possess aggregates which are less susceptible to disruption; due to the fact that plant roots remain are left intact in the NT soil after each cropping season unlike in the CT and RT system where tillage operation disrupt aggregate formation. Furthermore, soil tillage restricted to the planting rows in NT, warrant conditions for the preservation of fungal hyphae and favours the formation and distribution of soil macroaggregates; and consequently, increase nutrient availability and soil water retention (Wright *et al*., 2007). In addition, crop residues are left on soil surface in NT system, thereby improving organic matter content and organic matter derived binding agent which would enhance stability of soil aggregate. The removal of crop residues in CT system result to loss of soil organic matter which consequently, facilitates the aggregate breakdown processes thus explains the poor aggregate stability in these soils.

Higher proportion of all macroaggregates fractions >0.25 mm in cover crop soils may be attributed to higher root densities and better root system distribution in the cover crop soil relative to the bare soil with no cover crop. Consequently, favoring the binding of soil mineral particles (clay, silt, and sand) and the formation of stable aggregates, which indicates the importance of cover crops to improve soil aggregation. Furthermore, the presence of cover crop at the surface reduces slaking and disintegration of aggregates when wetted, thereby creating room for organic matter buildup and soil aggregate stability. Higher macroaggregates fractions in the surface soil could be attributed to higher organic matter content in the surface soil relative to sub-surface soil. Since surface soil is the immediate recipient of plant residues, therefore; organic matter generated from these plant residues is naturally high at the soil surface especially where crop residues are not incorporated or ploughed into soil as in the conventional tillage system. Presence of plant residues in soil encourages the activities of soil microbes especially bacteria in decomposing these residues and producing polysaccharides and other viscous microbial substances which resist dissolution by water thus binds microaggregates into macroaggregates (Weil and Brady, 2017). Furthermore, organic products of decay such as complex polymer chemically interact with particles of silicate clays and iron and aluminum oxides to form compounds which orient clays into pockets, which form bridges between individual soil particles, thereby binding them in water stable aggregates.

Higher fractal dimension (D) values in the RT and CT systems implies that these tillage practices had more fragmented soil aggregates than the NT system (Table 3). Higher D values are obtained with increasing fragmentation of soil (Tyler and Wheatcraft, 1989; Perfect and Kay, 1991) similarly Anderson *et al*. (1998) reiterated that large D values represent a highly fragmented soil with dominance of small aggregates. Furthermore, this is an indication that soil tillage renders soil aggregates less cohesive and unstable because pedoturbation by disc plough and shattering of soil peds by the disc harrow resulted in higher soil aggregates fragmentation and larger D values.

This finding is supported by that of Perfect *et al.* (2004), who investigated the effects of tillage treatments on mass fractal dimension for the soil moisture equation. They observed a significant difference in the values of D for tillage treatments with smaller values for No-till compared with those in the ploughed–disc treatment. This result corroborates those

Table 2. Tillage, cover crop and sampling depth effects on distribution of water stable soil aggregates at Samaru, Nigeria.

	←Sizes of soil aggregates fraction (mm)→					
Treatments	10-5	5-2	2-1	1-0.25	0.25-0.125	<0.125
Tillage (T)	← proportional weight of soil aggregates →					
No till (NT)	0.1311a	0.1328a	0.0314a	0.121	0.0889c	0.4978b
Reduced (RT)	0.1218ab	0.1088b	0.0269b	0.1180	0.1057b	0.5075ab
Conventional (CT)	0.1142b	0.1066b	0.0241b	0.1180	0.1193a	0.5261a
SE ±	0.004064	0.003009	0.001299	0.00131	0.003262	0.006804
Significance	*	**	**	NS	**	*
Cover Crops (C.)						
No Cover	0.1161	0.1119b	0.0219b	0.1155b	0.1097a	0.5153
Macrotyloma uniflorum	0.1259	0.1111b	0.0302a	0.1185ab	0.1062a	0.514
Centrosema pascorum	0.1232	0.1159b	0.0299a	0.1217a	0.1020ab	0.5137
Glycine max	0.1258	0.1137b	0.0281a	0.1190ab	0.1124a	0.5102
Cucurbita maxima	0.1207	0.1275a	0.0271a	0.1207a	0.0927b	0.4988
SE ±	0.005247	0.003885	0.001678	0.001687	0.004212	0.008784
Significance	NS	**	*	*	**	NS
Depth (cm) D						
0-5	0.1429a	0.1541a	0.0295a	0.1236a	0.0950b	0.4670c
5-10	0.1259b	0.1247b	0.0275a	0.1212a	0.0978b	0.5027b
10-15	0.1120c	0.1024c	0.0297a	1202a	0.1155a	0.5201b
15-20	0.1026c	0.0828d	0.0231b	0.1114b	0.1102a	0.5520a
SE ±	0.004693	0.003475	0.001501	0.00151	0.003767	0.007857
Significance	**	**	**	**	**	**
Interactions						
T x C	NS	**	**	NS	NS	NS
T x D	NS	**	**	*	NS	NS
D x C	NS	**	NS	*	NS	NS
T x D x C	**	**	*	*	NS	NS

Means followed by the same letter (s) within a treatment group are not significantly different at 5% level of significance using Duncan Multiple Range Test. SE = standard error, * Significant at $p \leq 0.05$, ** Significant at $p \leq 0.01$, NS = not significant.

Table 3. Effect of tillage, cover crop and depth on soil macro aggregate stability at Samaru, northern Nigeria.

Treatments	MWD	Log k (intercept)	D (Fractal dimension)	R^2	MiAOSMA
Tillage (T)					
No till (NT)	1.61a	2.518b	2.512b	0.94	0.5336a
Reduced (RT)	1.45b	2.531b	2.570a	0.952	0.5468a
Conventional (CT)	1.40b	2.579a	2.570a	0.950	0.4724b
SE ±	0.03132	0.00292	0.00224		0.00810
Significance	*	*	*		**
Cover Crops (C.)					
No Cover	1.426	2.524	2.690a	0.948	0.4899b
Macrotyloma uniflorum	1.491	2.561	2.419c	0.954	0.5196b
Centrosema pascuorum	1.482	2.517	2.510b	0.948	0.5171b
Glycine max	1.506	2.548	2.520b	0.946	0.5491a
Cucurbita maxima	1.511	2.566	2.520b	0.953	0.5203ab
SE ±	0.04041	0.03699	0.05850		0.01045
Significance	NS	NS	*		*
Depth (cm) D					
0-5	1.766a	2.627a	2.454709d	0.951	0.4775c
5-10	1.541b	2.563b	2.511886c	0.949	0.5082b
10-15	1.365c	2.52c	2.630268b	0.950	0.5498a
15-20	1.261d	2.434d	2.691535a	0.951	0.5349a
SE ±	0.03616	0.00391	0.00300		0.00935
Significance	*	*	*		**

Means followed by the same letter (s) within a treatment group are not significantly different at 5% level of significance using Duncan Multiple Range Test. SE = standard error, * = Significant at $p \leq 0.05$, ** = Significant at $p \leq 0.01$, NS = not significant, MWD = Mean Weight Diameter R^2 = coefficient of determination, MiAOSMA = Microaggregate occluded in stable macroaggregate

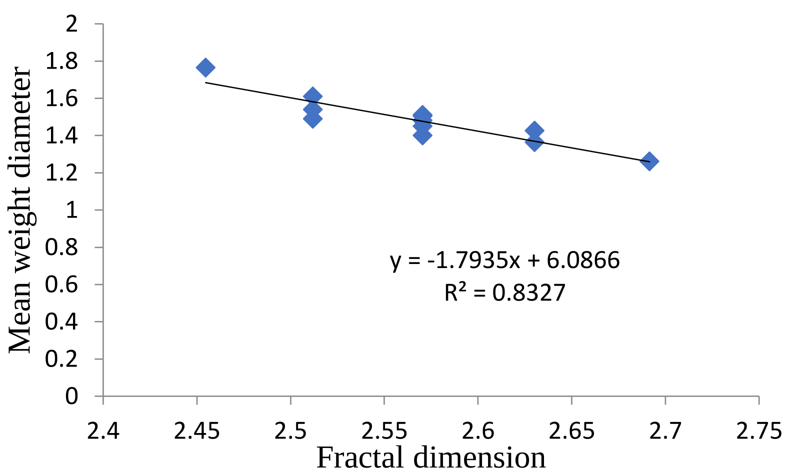

Figure 1. Relationship between mean weight diameter and fractal dimension.

reported by Perfect and Blevins (1997); Pirmoradian *et al*. (2005) and Tripathi *et al*. (2012) they showed that fractal parameter can be used to characterize both soil aggregation and fragmentation, and this parameter is sensitive to tillage treatment. According to their results, Mould board plus disc ploughing increased soil fragmentation in comparison with no-till. This effect was partially reversed by secondary cultivation, indicating that discing broke up large clods and/or coalesced small fragments produced by mould board ploughing.

Expectedly, the lower values of D in soils with cover crops could be attributed to the abundance of roots in these soils, which could have contributed to the clustering of soil aggregates (less fragmentation) relative to the bare plots with no cover crops which were most fragmented. This inference finds evidence in the work of Salako *et al.* (1999) that indicated live mulching with *Pueraria* was responsible for numerical less fragmentation of soil aggregate despite continuous cropping. Furthermore, abundance of crop residue in cover crop soils could create room for increased microbial activity in producing microbial derived binding agents for soil aggregates thus higher macroaggregate proportion and improved soil aggregate stability.

Furthermore, the abundance of roots in soils under cover crops probably promoted the release of exudates, known as polysaccharides, cementing substances, which are responsible for stabilizing soil particles, these cementing substances are also interwoven with fungal hyphae and roots of cover crops and contribute to increase in the activity of microorganisms in the soil, especially Arbuscular Mycorrhiza Fungi (Rillig and Mummey, 2006), This soil biota activity influences the soil structure and, consequently, increases the aggregate stability.

The higher organic matter content at the top soil, which often times, recede with soil depth, could be responsible for better soil aggregation (MWD) and lower values of D (less fragmentation of soil aggregates) at the top soil (0-5 cm).
The variation of fractal parameters with the tillage and cover crop treatments and at the different soil sampling depth, suggests that fractal dimension is another useful index for evaluating soil structural stability. This had earlier been documented by some authors (Young and Crawford, 1991; Burrough, 1993; Crawford and Matsui, 1996; Kozak *et al.*, 1996; Anderson *et al.*, 1997; Salako *et al*, 1999).

The intercepts (log k) of the regression graph between of log x (mean sieve sizes) versus log N (number of aggregates retained on each sieve) can be used as an index of the abundance of fragmented soil aggregates in a given mass, Eghball *et al.* (1993) used them in a fractal analysis to indicate the abundance of roots. Generally, data obtained in this study showed that the intercepts (log *k*) were influenced more by the number of aggregates retained on sieves >0.10 mm diameter, thereby suggesting that invariably, the number of aggregates making up the macro aggregates was particularly reflected by the intercepts. While the high r^2 value values (between 0.94 and 0.97) in the regression plots suggest that the data were adequately described by fractal analysis.

The higher proportion of MiAOSMA in NT and RT soil is an indication that non and minimal soil disturbance improve soil macroaggregate structure and stability, since MiAOSMA contain physically protected organic matter from microbial decomposition; MiAOSMA is therefore key to improve C sequestration. Similarly, enhanced C sequestration through C stabilization within the microaggregates occluded in macroaggregates has been confirmed in afforested (Six *et al*. 2002; Del Galdo *et al*. 2003) and forested soils (Six *et al*. 2002) compared to agricultural soils where tillage operation was carried out.

The broader leaves, thus higher leaf area in both *Glycine max* and *Cucurbita maxima* relative to other cover crops may be useful in sequestering C thereby offering better protection for MiAOSMA and stability of macroaggregate in the soils of these two cover crops. In addition, the biodegradability of *Glycine max* and *Cucurbita maxima* crop residues and microbial activity generated after their addition, could generate stabilizing substances such as polysaccharides and hydrophobic compounds or motivate the development of efficient stabilizing microorganisms like filamentous fungi thereby increase the proportion of MiAOSMA and stability of macroaggregate. High clay content in lower soil depths due to illuviation may be responsible for significantly higher MiAOSMA at these soil depths.

CONCLUSION

Conservation till (NT and RT) systems and cover cropping better enhanced soil aggregate stability due to better accumulation of organic matter emanating from crop residues return to soil in these practices. The strong linear relationship established between MWD and fractal dimension and the significant fragmentation (D) revealed amongst tillage treatments, indicates that fractal theory of soil aggregates using the cumulative number approach showed significant differences in stability of soil aggregates. Therefore, suggesting that fractal dimension is another useful index for evaluating soil aggregate stability.

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REFERENCES

Anderson, A.N., McBratney, A.B. and Crawford, J.W., 1997. Applications of fractals to soil studies. *Advances in Agronomy*, 63, pp. 1-76. https://doi.org/10.1016/S0065-2113(08)60241-2

Anderson, J.M. and Ingram, J.S.I. (eds) 1993. Tropical soil biology and fertility: A hand book of Methods 2nd edition. C.A.B International Wallingford, UK. pp. 221. In: *Soil Science* 157(4), pp. 265. April 1994. https://doi.org/10.2307/2261129

Angers, D.A. and Mehuys, G.R., 1993. Aggregate stability to water. In: *Soil sampling and methods of analysis*, Carter M.R, Ed., Canadian Society of soil science.

Baldock J.A. and Kay, B.D., 1987. Influencing of cropping history and chemical treatment on the water-stable aggregation at a silt loam soil. *Canadian Journal of Soil Science*, 67, pp. 501–511. https://doi.org/:10.4141/CJSS87-047

Blanco-Canqui, H. and Lal R., 2004. Mechanisms of carbon sequestration in soil aggregates. *Critical Reviews in Plant Sciences*, 23, pp 481–504. http://dx.doi.org/10.1080/07352680490886842

Bremner, J.M. and Mulvaney, C.S., 1982. Nitrogen—Total. p. 595–624. AL Page et al.(ed.) *Methods of soil analysis*. Part 2. Agronomy Monograph. 9. ASA and SSSA, Madison, WI. Nitrogen—Total. pp. 595–624. In AL Page et al.(ed.) Methods of soil analysis. Part 2. 2nd ed. Agronomy Monograph. 9. ASA and SSSA, Madison, WI. https://doi.org/10.2134/agronmonogr9.2.2ed.c31

Burrough, P.A., 1993. Soil variability: a late 20th century view. *Soils Fertility*, 56, pp.529-562.

Crawford, J.W. and Matsui, N., 1996. Heterogeneity of the pore and solid volume of soil: distinguishing a fractal space from its non-fractal complement. *Geoderma*, 73, pp. 183–195. https://doi.org/10.1016/0016-7061(96)00045-6

Del Galdo, I., Six, J., Peressotti, A. and Cotrufo, M.F., 2003. Assessing the impact of land-use change on soil C sequestration in agricultural soils by means of organic matter fractionation and stable isotopes. *Global Change Biology*, 9, pp.1204–1213. https://doi.org/10.1046/j.1365-2486.2003.00657.x

Eghball, B., Mielke, L. N., Calvo, G.A. and Wilhelm, W.W., 1993. Fractal description of soil fragmentation for various tillage methods and crop sequences. *Soil Science Society of American Journal*, 57, pp.1337-1341. https://doi.org/10.2136/sssaj1993.03615995005700050029x

Elliott, E.T., 1986. Aggregate structure and carbon, nitrogen and phosphorus in native and cultivated soils. *Soil Science Society American Journal*. 50, pp. 627 – 633. http://dx.doi.org/10.2136/sssaj1986.03615995005000030017x

Gee, G.W. and Or, D., 2002. Particle size analysis. In: Dane, J.H., Topp, G.C. (eds.), *Methods of Soil Analysis*, Part 4. Physical Methods. Soil Science Society America. Book Series No. 5, American Society of Agronomy and Soil Science Society of America, Madison, WI, pp. 255–293. https://doi.org/10.2136/sssabookser5.4.c12

Grossman, R.B. and Reinsch, T.G., 2002. Bulk density and linear extensibility. In: Dane, J.H., Topp, G. C. (eds), *Methods of Soil Analysis*, Part 4. Physical Methods. Soil Science Society America. Book Series No. 5, American Society of Agronomy and Soil Science Society of America, Madison, WI, pp. 201–228. https://doi.org/10.2136/sssabookser5.4.c9

Jones, M.J. and Wild, A., 1975. Soil of the West African savanna; T*echnical communication of the Common Wealth Bureau of soils* No. 55, Common Wealth Agricultural Bureau. Harpenden. UK. https://doi.org/10.1177/030913337700100122.

Kozak, E., Pachepsky, Y.A., Sokolowski, S., Sokolowska, Z. and Stepniewski, W., 1996. A modified number-based method for estimating fragmentation fractal dimensions of soil. *Soil Science Society American Journal*, 60, pp. 1291–1297. https://doi.org/10.2136/sssaj1996.03615995006000050002x.

Kemper, W.D. and Rosenau, R.C., 1986. Aggregate stability and size distribution. *Methods of soil analysis*: Part 1 Physical and mineralogical methods, 5, pp. 425-442. https://doi.org/10.2136/sssabookser5.1.2ed.c17

Masri, Z. and Ryan, J., 2006. Soil organic matter and related physical properties in a Mediterranean wheat-based rotation trial. *Soil and Tillage Research*, 87, pp. 146 – 154. https://doi.org/10.1016/j.still.2005.03.003

Mazurak, A.P., 1950. Effect of gaseous phase on water-stable synthetic aggregates. *Soil science*, 69, pp. 135 – 148. https://doi.org/10.1097/00010694-195002000-00005

Mandelbrot, B.B. and Mandelbrot, B.B., 1982. The fractal geometry of nature (Vol. 1). New York: WH freeman. https://doi.org/10.2307/2323761

McCartney, A. B., 1993. Comments on fractal dimension of soil aggregate-size distribution calculated by number and mass. *Soil Science Society of America Journal*, 57, pp. 1393. https://doi.org/10.2136/sssaj1993.03615995005700050038x

Mclean, E.O., 1982. Soil pH and lime requirement. In: Page, A.L. (ed.), *Methods of Soil Analysis*, Part II, 2nd ed., America Society of Agronomy Monograph No. 9. Madison, WI, pp. 199–224. https://doi.org/10.2134/agronmonogr9.2.2ed.c12

Nelson D.W. and Sommers, L.E., 1982. Total Carbon, Organic Carbon and Organic Matter. In Page, A.: Miller, R.H and Keeney, D.R (eds) *Methods of Soil Analysis* II American Society of Agronomy Madison NY, pp. 539-579. https://doi.org/10.2134/agronmonogr9.2.2ed.c29

Oluwasemire, K.O. and Alabi, S. O., 2004. Ecological impact of changing rainfall pattern, soil processes and environmental pollution in the Nigerian Sudan and northern Guinea savannah agro-ecological zones. *Nigerian Journal of Soil Research*,. 5, pp. 23-31. https://www.abu.edu.ng/njser ISSN 1595 – 61 21.

Perfect, E. and Kay, B.D., 1991. Fractal theory applied to soil aggregation. *Soil Science Society of America Journal* 55, pp. 1552-1558. https://doi.org/10.2136/sssaj1991.03615995005500060009x

Perfect, E., Rasiah, V. and Kay, B. D., 1992. Fractal dimension of soil aggregate-size Distributions calculated by number and mass. *Soil Science Society of American Journal*, 56, pp. 1407-1409. https://doi.org/10.2136/sssaj1992.03615995005600050012x

Perfect, E. Kay, B.D. and Rasiah, V., 1993. Multifractal model for soil aggregate fragmentation. *Soil Science Society of America Journal*, 57, pp. 896–900. https://doi.org/10.2136/sssaj1993.03615995005700040003x

Perfect, E., Kay, B.D. and Rasiah, V., 1994. Unbiased estimation of the fractal dimension of soil aggregate size distribution. *Soil and Tillage Research*, 31, pp. 187–198. https://doi.org/10.1016/0167-1987(94)90079-5

Perfect, E., Kenst, A. B., Diaz-Zorita, M. and Grove, J. H., 2004. Fractal analysis of soil water desorption data collected on disturbed samples with water activity meters. *Soil Science Society of America Journal*, 68, pp. 1177–1184. https://doi.org/10.2136/sssaj2004.1177

Perfect, E. and Blevins, R. L., 1997. Fractal characterization of soil aggregation and fragmentation as influenced by tillage treatment. *Soil Science Society of America Journal*, 61, pp. 896–900. https://doi.org/10.2136/sssaj1997.03615995006100030026x.

Pirmoradian, N., Sepaskhah, A.R. and Hajabbasi, M.A., 2005. Application of Fractal Theory to quantify Soil Aggregate Stability as influenced by Tillage Treatments. *Biosystems Engineering*, 90 (2), pp. 227–234. https://doi.org/10.1016/j.biosystemseng.2004.11.002

Rasiah, V., Kay, B.D. and Perfect, E., 1992. Evaluation of selected factors influencing aggregate fragmentation using fractal theory. *Canadian Journal of Soil Science*, 72, pp. 97-106. https://doi.org/10.4141/cjss92-009.

Rasiah, V., Kay, B.D. and Perfect, E., 1993. New mass-based model for estimating fractal dimension of soil aggregates. *Soil Science Society of America Journal*, 57, pp. 891–895. https://doi.org/10.2136/sssaj1993.03615995005700040002x

Rasiah, V. and Biederbeck, V. O., 1995. Fractal dimension of soil aggregation: influence of bulk density, fitting procedure, and oily waste sludge incorporation. *Soil Science*, 160 (4), pp. 250–255. https://doi.org/ 10.1097/00010694-199510000-00003

Rasiah V; Perfect E. and Kay, B.D., 1995. Linear and nonlinear estimates of fractal dimension for soil aggregate fragmentation. *Soil Science Society of America Journal*, 59, pp. 83–87. https;//doi.org10.2136/sssaj1995.036159950 05900010012x

Rillig, M. C. and Mummey, D. L., 2006. Mycorrhizas and soil structure. *New Phytol*, 171, pp. 41-53. https://doi.org/10.1111/j.1469-8137.2006. 01750.x

Rieu, M. and Sposito, G., 1991a. Fractal fragmentation, soil porosity, and soil water properties: theory 1. *Soil Science Society of American Journal*, 55, pp. 1231-1238. https://doi//org/10.2136/sssaj1991.03615995 005500050007x

Rieu, M. and Sposito, G., 1991b. Fractal fragmentation, soil porosity, and soil water properties. 2: Applications. *Soil Science Society of American Journal*, 55, pp. 1239-1244. https://doi//org/10.2136/sssaj1991.03615995 005500050006x

Rhodes, J.D., 1982. Cation Exchange Capacity, In: Page, A.L and Miller R.H. (ed.). *Method of Soil Analysis* 2. Second edition. Agronomy Monogram. pp. 149-157. ASA and SSSA, Madison, WI. https://doi.org/10.2134/agronmonogr9.2.2ed.c8

Salako, F. K., Babalola, O., Hauser, S. and Kang, B. T., 1999. Soil macroaggregate stability under different fallow management systems and cropping intensities in southwestern Nigeria. *Geoderma*, 91 (1-2), pp. 103-123. https://doi.org/10.1016/S0016-7061(99)00006-3

SAS Institute, SAS/STAT User's Guide (Version 9.2), Statistical Analysis System Inst, Cary, NC, USA,

Sepaskhah, A., Mousavi, S. and Boersma, L., 2000. Evaluation of fractal dimensions for analysis of aggregate stability. *Iran Agricultural Research*, 19 (2), pp. 99-114. https://www.sid.ir/en/journal/ViewPaper.asp x?id=115727

Six, J., Elliott, E.T. and Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, 32 (14), pp. 2099–2103. https://doi.org/10.1016/S0038-0717(00)00179-6

Six, J., Callewaert, P., Lenders, S., De Gryze, S., Morris, S.J., Gregorich, E.G., Paul, E.A. and Paustian, K., 2002. Measuring and understanding carbon storage in afforested soils fractionation. *Soil Science Society America Journal*, 66, pp. 1981– 1987. https://doi.org/10.2136/sssaj20001981

Tripathi, S. K., Kushwaha, C. P. and Basu, S. K., 2012. Application of fractal theory in assessing soil aggregates in Indian tropical ecosystems. *Journal of Forestry Research*, 23 (3), pp. 355-364. https://doi.org/10.1007/s11676-012-0271-3.

Turcotte, D.L., 1986. Fractal and fragmentation. *Journal of Geophysics Research*, 91, pp. 1921–1926. https://doi.org/10.1029/JB091iB02p01921

Tyler, S.W. and Wheatcraft, S.W., 1989. Applications of fractal mathematics to soil water estimation. *Soil Science Society of America Journal*, 53, pp. 987–996. https://doi.org/10.2136/sssaj1989.03615995 005300040001.x

van Bavel, C.H.M., 1949. Mean weight-diameter of soil aggregation as a statistical index of aggregation. *Soil Science Society of America Journal*, 14, pp. 20–23. https://doi.org/10.2136/sssaj1950.03615995 0014000C0005.x

Weil, R.R. and Brady, N.C., 2017. *The nature and properties of soil*. 15th edition Pearson Education limited, Edinburgh Gate, Harlow, Essex CM20 2JE, England, pp. 1071.

Wright, S. F., Green, V.S. and Cavigelli, M.A., 2007. Glomalin in aggregate size classes from three different farming systems. *Soil and Tillage Research*, 94, pp. 546-549. https://doi.org/10.1016/j.still.2006.08.003

Young, I.M., Crawford, J.W., 1991. The fractal structure of soil aggregates: its measurement and interpretation. *Journal of Soil Science*, 42, pp. 187–192. https://doi.org/10.1111/j.1365-2389.1991.tb00400.x