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CHANGES IN SOIL AGGREGATE STABILITY AND CARBON SEQUESTRATION MEDIATED BY LAND USE PRACTICES IN A DEGRADED DRY SAVANNA ALFISOL

[CAMBIOS EN LA ESTABILIDAD DEL SUELO Y SECUESTRO DE CARBONO MEDIADO POR LAS PRÁCTICAS DE USO DE SUELO EN UN ALFISOL DE SABANA SECA DEGRADADA]

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SUMMARY

Effects of land use practices on aggregate stability and fractions of soil organic carbon were investigated using the physical fractionation procedure. Soils were sampled at three depths (0-5; 5-15 and 15-25cm) under arable cropping, native vegetation and forest. These soils were separated into aggregates to calculate mean weight diameter (MWD) and aggregate associated carbon. Results showed that MWD increased in soils under forest by 61.4% relative to the soils under arable cropping practice. The macroaggregate fraction in the forested soils was 76.2% more than those soils under arable cropping. Chemically protected carbon was higher by 39% in soil under arable cropping compared to forested soils. Forest plantations therefore, may have potential to increase the structural stability of soils and their resistance to soil erosion. Arable cropping seems to favor increasing carbon sequestration relative to native vegetation and Eucalyptus forested soils.

Keywords: Land use; carbon sequestration; forest; Eucalyptus; native vegetation; arable cropping.

RESUMEN

Se investigaron los efectos de las prácticas de uso del suelo en la estabilidad de los agregados del suelo y se analizaron fracciones del carbono orgánico del uselo empleando procedimiento de fraccionamiento físico. Se muestreo el suelo a tres profundidades (0-5, 5-15 y 15-25 cm) en suelo cultivado, con vegetación nativa y en bosque. Los suelos fueron separados en agregados para calcular el diámetro medio (MWD) y carbono asociado al agregado. Los resultados mostraron que el MWD incrementó 61.4% en suelo del bosque en relación al suelo de áreas de cultivo. La fracción de macroagregados en los suelos de bosque fue 76.2% mayor que los suelos del área de cultivo. Carbono químicamente protegido fue mayor (39%) en suelos cultivados en comparación con los suelos de bosque. Se que concluye que los plantaciones forestales tienen el potencial de incrementar la estabilidad estructural de los suelos y su resistencia a la erosión. Las áreas de cultivo parecen favorecer el secuestro de carbono en relación a la vegetación nativa y los suelos de bosque de Eucalipto.

Palabras clave: Uso del suelo; secuestro de carbon; bosque; Eucalipto; vegetación nativa; cultivos.

INTRODUCTION

The conservation and proper management of soil organic matter (SOM) is essential to soil functions in any ecosystem. This is because SOM provides services which can be described both as ‘soil fertility’ and ‘environmental’ functions from the perspective of farmers and the society respectively (Feller *et al.* 2001a). Appropriate management of SOM ensures soil fertility and minimizes agricultural impact on the environment through carbon sequestration, erosion control and preservations of soil biodiversity (Six *et al.* 2002). Loss of SOM will therefore reduce soil fertility, degrade soil structure and water holding capacity and ultimately, leads to land degradation.

Land degradation and the effects of SOM loss are particularly critical in arid, semi arid and partially dry sub humid areas of the tropical regions, where the risk of desertification is great. Reduction in precipitation and increase in temperature associated with global warming further undermine the integrity of these ecosystems. One effect of global warming will be to accelerate SOM decomposition thereby, releasing carbon dioxide (CO_2) to the atmosphere, which will further enhance the warming trend (Jenkinson *et al*. 1991). Carbon exchange between the terrestrial biosphere and the atmosphere is therefore, one key process that needs to be assessed in the context of the Kyoto protocol and post-Kyoto agreements.

Land use and land use changes are widely recognized as key drivers of the global carbon dynamics. Good and appropriate land use practices have the ability to substantially increase potential carbon sink in soils. In the past, farmers in dryland ecologies (particularly, in West Africa) have succeeded in maintaining a level of agro-ecological equilibrium through the cropping pattern and rotational agriculture, practiced with a 5-10 year fallow (Ganry *et al*. 2001). The equilibrium was maintained with the traditional agroforestry systems practiced. However, increased radiative forces arising from anthropogenic emission of gases to the atmosphere, along with population increases and reduced fallow periods upset the balance. Land use changes, such as afforestation, reforestation, grazing and conversion of natural to managed ecosystem therefore, act to alter SOM, by both build up and decomposition.

Correct management and restoration of degraded soils is necessary in order to reverse the negative effects and to protect ecosystems. Afforestation of degraded lands can potentially enhance carbon sequestration (Johnson, 1992). Forest in the United States has been reported to be responsible for much of the North America's carbon sink (Woodbury *et al*. 2007). Studies of soil ecosystems under forest in temperate regions have demonstrated the substantial increase noticeable in total organic carbon and intra-aggregate particulate organic carbon fraction relative to the agricultural ecosystems (Six *et al*. 2002).

There exist complex interactions between soil organic carbon storage and aggregate stability (Feller, *et al*. 2001b). Aggregation is one significant pedospheric process that facilitates carbon sequestration in soil. This is made possible through the formation of stable organo-mineral complexes. Soil organic carbon, on the other hand, can encapsulate within stable aggregate thereby offering protection against microbial processes and enzymatic reaction (Lal, *et al*. 2003; Holeplass *et al*. 2004). Although a number of previous studies has dealt with aggregate stability under No-tillage (Six *et al*. 2004; Denef *et al*. 2007) and grazing management (Conant *et al*. 2002; Goberna *et al*. 2006), relatively few studies have examined aggregation and soil organic carbon interaction under tropical environment. The main objective of this study was to determine land use practice that improve the quality of a degraded soil through analysis of aggregate stability, soil fertility and carbon storage in a natural, (af)forested and cultivated ecosystems.

MATERIAL AND METHODS

Study site

This comparative study was done at the Afaka Forest Reserve of Kaduna (latitude 10^o 33' to 10^o 40'N and longitude 07^o 15'E), Northern Guinea Savanna zone of Nigeria. The climate of the study area is a sub-humid tropical, with a long-term mean annual precipitation of 1270mm, of which 90% is received during May to October. Mean monthly minimum and maximum temperature ranges from 20 and 12^oC in December and to 35 and 28^oC in April, respectively. The topography is almost plain (nearly leveled) with <2% slope. The soil type is Alfisols; Plinthustalfs, sandy loam and it is relatively eroded with patches of protruding reddish B-horizon exposed to the surface. The Forest Reserve covers an area of 700 ha planted to various forest tree species. In the area calved out as research plot within the forest reserve, *Eucalyptus camadulensis* was planted on a 2.2 ha land area and; adjacent to this plot is an expanse of land under natural fallow (Native vegetation) of predominantly, *Andropogon gayanus* interspaced by *Isoberlinia doka*. These two sites have been maintained since 1987 (*i.e.*, 19 years prior to sampling). A portion of the land under native vegetation was put under continuous cultivation since 1992 using traditional (manual) tillage for cropping maize, sorghum and cowpea. These three land use practices (forested, native vegetation and arable cropping) form the treatments for the study.

Field sampling

The research plot in the forest reserve was designed at the onset, to minimize the impact of spatial heterogeneity in field soils in order to enhance the efficiency of the analysis of variance. A stratified random sampling (Petersen and Calvin, 1986) that divides the sampling plot into three subdivisions (or replicates) was therefore, adopted to sample soils. At each sampling location, bulk soils were collected at three depths; 0-5cm, 5-15cm and 15-25cm using a traditional hoe and a bucket auger. For each replicate treatment, soils were sampled from four randomly selected sites and bulked to produce a composite sample. This is to increase the precision of estimate over the entire population, as soils of each replicate were relatively in a homogeneous domain. Once in the laboratory, the field moist composite samples were divided into two halves; one half was passed through a 5-mm sieve by gently breaking apart the soil. These sieved samples were composited per replicate and for each depth, before air-drying and storage at room temperature. The second half was air-dried, crushed through a 2-mm sieve and stored for use in routine laboratory analysis.

Routine laboratory analysis

The air-dried 2-mm sieved soil samples were used for the analysis of soil pH in 1:2.5 soil/water suspensions with the aid of a glass electrode pH meter. Particle size distribution was determined by the hydrometer method and sodium hexametaphosphate as dispersant (Gee and Bauder, 1986). The Kjeldahl digestion procedure of Bremner and Malvaney (1982) was used to determine soil nitrogen content. The Bray 1 extraction method (Bray and Kurtz, 1945) was used to extract available phosphorus from the soil, and determined colorimetrically by the ascorbic acid method (Murphy and Riley, 1962). Exchangeable cations were extracted in neutral normal (1N) ammonium acetate (pH 7) solution. Ca^{2+} and Mg^{2+} in solution were determined using the Atomic Absorption Spectrophotometer (using Acetylene flame and Lithium salt) while, K^+ and Na^+ were determined with the flame emission photometer. For the determination of soil organic carbon, the Walkley-Black wet oxidation method (Nelson and Sommers, 1982) was adopted.

Water stable aggregate

A 200g sub sample was taken from the 5mm sieved soil and aggregate were separated by wet sieving after rapid immersion. Four aggregate fractions were obtained: >2mm (referred to as large macroaggregates) 0.25 – 2mm (small macroaggregates), 0.053-0.25mm (microaggregates) and <0.053mm (silt + clay fraction). All fractions were oven dried for 24 hours (60^{o}C) and stored at room temperature. Except for the large macroaggregates, all other aggregate fractions were corrected for different sand contents before comparision. The >2mm fraction was too small in weight to determine sand content.

The mean weight diameter (MWD) was calculated using all aggregate fractions corrected for sand, as:

$$MWD_{(mm)} = \frac{2+0.25}{2}[A] + \frac{0.25+0.053}{2}[B] + \frac{0.053}{2}[C]$$

Where [A], [B] and [C] are weight percentages of small macroaggregates, micro aggregates and silt + clay fractions respectively.

Carbon analyses

Organic carbon (C) was analyzed through the wet oxidation method of Nelson and Sommers (1982) for all three aggregate fractions namely; 0.25-2mm (referred to as unprotected carbon); 0.053-0.25mm (physically protected carbon) and; <0.053mm (chemically protected carbon). Sand-free carbon concentration was calculated in the aggregate fractions greater than 0.053mm (Denef et al. 2007) as:

$$\text{Sand-free } C_{fraction} = \frac{C_{fraction}}{[1 - (\text{Sand proportion})_{fraction}]}$$

Acid hydrolysis was employed to determine the non-hydrolyzable carbon (Tan *et al*. 2004). In brief, 1 gm of 0.25mm sieved composite soil sample was digested in 25mls of 6N HCl (Paul *et al*. 2001) at 100^{o}C until only soil residue was left. Thereafter, HCl was removed by washing and centrifuging the residue twice with 40 mls distilled water. The final residue was oven dried (60^{o}C) for 12 hours and the non-hydrolyzable carbon was determined by wet oxidation. This carbon fraction is hereafter referred to as biochemically protected carbon. In the course of wet sieving, substantial amount of soluble carbon would have been dissolved in water; we did not determine this carbon fraction because our interest is carbon sequestered in water stable aggregates.

Statistical analysis

To determine the influence of land use practice and depth on the measured properties (water stable aggregate, aggregate associated carbon, etc), general linear model (GLM) analysis of variance (ANOVA) was used. To compensate for variance heterogeneity; values for aggregate associated (unprotected, physically-, chemically- and biochemically-protected) carbon were logarithm-transformed before data analysis. Differences between land use practices and depth were tested with Duncan Multiple Range Test (DMRT). All analyses were performed with SAS (1987) computer package.

RESULTS

Soil fertility

There was no significant treatment difference in soil pH, exchangeable sodium (Na^+), potassium (K^+) and magnesium (Mg^{2+}) (Table 1). The soil ranged from strongly acid to very strongly acid. The most predominant effect of land use on soil organic carbon and soil nitrogen was observed in soils under the arable cropping practice. The native vegetation recorded more soil nitrogen than the forested system. Soils under forest recorded significantly ($P < 0.05$) higher values of available P and exchangeable K than those under arable cropping and native vegetative (Table 1). Exchangeable Ca^{2+} and Na^+ were lowest in soils under the forest systems. Except for organic carbon, soil nitrogen, soil pH and Ca^{2+}, where 0-5cm soil depth recorded significantly ($P < 0.001$) higher values than the other two; there was no significant difference in depth distribution for the other parameters.

Soil aggregate stability

Both mean weight diameter (MWD), large- and small- macroaggregate fractions recorded no significant depth influence. However, microaggregate and silt + clay fractions recorded significant ($P < 0.05$) differences along soil depth (Table 2). Changes in land use practices influenced MWD and all aggregate fractions (except for silt + clay fraction); forest soils had higher MWD and small macro-aggregate values than the other two practices. Values of MWD and small macroaggregate fraction were lowest under the arable cropping practices. Native vegetation recorded significantly higher large macroaggregate fraction however, soils under arable cropping recorded the highest value of micro aggregate fraction and this was significantly ($P < 0.05$) higher than those of the other two. There was no significant difference in the proportion of microaggregate fraction of the other two land use practices. The silt + clay fraction as expected was not significantly influenced by land use practices (Table 2).

Table 1: Influence of land use practices and soil depth on the fertility of a savanna Alfisol

Depth (cm)	TOC	TSN	AP	pH Water	K	Na	Ca	Mg	Sand	Silt	Clay
					(cmol kg^{-1})				%		
0-5	13.50a	1.08a	8.56	5.91a	0.23	0.24	2.47a	1.189	56.81a	24.97	18.22c
5-15	11.30b	0.73b	8.07	4.87b	0.19	0.25	2.42a	1.000	50.59b	25.08	24.33b
15-25	9.00c	0.55b	7.78	4.56b	0.19	0.30	1.87	1.022	47.92b	24.52	27.11a
SE	0.683	0.062	0.522	0.114	0.0192	0.0183	0.104	0.11	1.938	1.34	0.92
Land use											
Native Vegetation	10.50b	0.77ab	8.17ab	5.17ab	0.204b	0.304a	2.53a	1.12	53.7a	20.52b	25.78a
Forest ecosystem	9.93b	0.66b	9.33a	4.89b	0.266a	0.209b	1.711b	0.96	56.14a	19.52b	23.89a
Arable cropping	13.37a	0.94a	6.90b	5.28a	0.193c	0.274a	2.511a	1.13	45.48b	34.52a	20.00b
SE	0.683	0.062	0.522	0.114	0.0192	0.0183	0.104	0.11	1.938	1.34	0.92

Means followed by different letter(s) within the same column are significant at 5% level of probability
TOC g kg^{-1}- Organic carbon, TSN g kg^{-1}- Soil nitrogen, AP mg kg^{-1}-Available phosphorus, K mg kg^{-1}-Exchangeable potassium, Na-Exchangeable sodium, Ca-Exchangeable calcium
SE- Standard error

Table 2: Fractions of aggregates and mean weight diameter (MWD) as affected by land use practices and depth

Depth (cm)	MWD	Large- Macro-aggregates	Small macroaggregate	Microaggregates	Silt+clay
0-5	0.414	0.175	0.321	0.311a	0.192a
5-15	0.455	0.208	0.364	0.263b	0.166b
15-25	0.443	0.248	0.356	0.248b	0.149b
SE	0.0302	0.0394	0.0251	0.0159	0.0071
Land use					
Native vegetation	0.436b	0.277a	0.352b	0.229b	0.146
Forest ecosystem	0.539a	0.129b	0.437a	0.270b	0.158
Arable cropping	0.334c	0.224ab	0.248c	0.323a	0.203
SE	0.0302	0.0394	0.0251	0.0159	0.0071
Interaction	NS	Ns	NS	NS	NS

Means followed by different letter(s) within the same column are significant at 5% level of probability
SE - Standard error

Soil organic carbon pools

The various fraction of sand free organic carbon were significantly affected by soil depth (Table 3). The 0-5cm soil depth recorded the highest accumulation of the free-, protected- and non-hydrolyzable- carbon fractions and, these values reduced gradually with increasing soil depth. When land use effect on soil organic carbon pools were evaluated, the chemically protected organic carbon pool was significantly (P = 0.05) higher in soil under arable than the values for the other two practices. However, for the other carbon pools, there was no significant treatment effect on them (Table 3).

DISCUSSION

Perceptible changes in soil fertility as a result of land use practices revealed a low to moderate soil organic carbon content. Soils under the arable cropping systems recorded moderate organic carbon status. Its nitrogen status was also higher than those of the other two soil management practices. The annual application of mineral fertilizers to the arable cropping system must have been responsible for its high carbon and nitrogen content relative to the others. In addition, annual crops have the tendency to translocate relative higher amount of photosynthates to the under-ground zone than tree crops. Many long term trials have affirmed that soil organic carbon is increased by the application of mineral fertilizers (Cuvardic *et. al*. 2004). Land use practices did not improve considerably the available phosphorus content of these soils. Although, the available soil phosphorus was generally low, the soils under forest enhance phosphorus by 14% and 35% respectively over native vegetation and arable cropping systems. Forest tree crops, with their rooting system, have the tendency to extract P from deeper layers of the soil. Soil potassium (K) content was high under forest, moderate with native vegetation and low with arable cropping. This observation is an indication that continuous cropping can accelerate K mining from soil. Forested systems appeared to have a slight pH depressive effect on their soils. Organic acids released from the biomass of forest trees may be a probable reason for the pH depression in these soils. The increase in Ca^{2+} status in arable soils may be due to input management practices which must be contributions from the crop residue incorporation during annual land preparation.

Results of the field trial indicate that land use can significantly affect aggregate size distribution and stability. Soils under native vegetation and forest were better structured than those under arable cropping. Perturbation of soil during cropping may have destroyed soil aggregates and adversely affected the structure of soils under arable cropping system. Beare *et al* (1994) demonstrated that cultivation of soils will lower the structural stability relative to the no-tillage soil; particularly where crop residue removal is practice as it is in this case. The continuous deposition of biomass through leaf falls in the forest can also enhance improvement in soil aggregation and aggregate stability. The significant proportion of large macroaggregate (> 2.0 mm) in the native vegetation and arable cropping could be as a result of disturbance-induced increase in macroaggregate turnover.

Table 3: Influence of land use practices and soil depth on the distribution of various forms of carbon (gkg^{-1}) of a savanna Alfisol

Depth (cm)	Free (unprotected) carbon	Physically protected carbon	Chemically protected carbon	Non-hydrolyzable carbon
0-5	30.2a	22.39a	13.71a	7.10a
5-15	18.62b	18.20a	10.99ab	4.57b
15-25	12.30b	11.48b	8.26b	3.32c
SE	0.064	0.0395	0.04121	0.0382
<u>Land use</u>				
Native vegetation	18.20	15.49	11.22ab	4.38
Forest ecosystem	19.06	16.22	8.93b	4.69
Arable cropping	19.95	18.62	12.42a	5.25
SE	0.064	0.0395	0.04121	0.0382
Interaction	NS	NS	NS	NS

Means followed by different letter(s) within the same column are significant at 5% level of probability
SE - Standard error

Six *et al*. (1998) linked a proportion of carbon lost upon disturbance (e.g. tillage, trampling etc) to an increase turnover of macroaggregates. Although, this disturbance increased macro-aggregate turnover, it inhibits the formation of microaggregates within macro-aggregate and therefore reduced long-term sequestration of carbon within micro-aggregates (Six *et al*. 2004). The significantly high proportion of micro-aggregate (not occluded in macroaggregates) in soil of arable cropping system add credence to this fact. The microaggregate fraction is easily removed during soil erosion by water (Adesodun *et. al*. 2005). This observation is an indication that arable cropping systems will be more susceptible to water erosion than the other two practices. In addition, greater changes in aggregate size distribution or stability were not detected along soil depth. However, significant proportion of microaggregate and silt plus clay fractions at the soil surface is an indication that the surface soil (0-5cm) will be more vulnerable to soil loss by water erosion than the lower layers.

Soil carbon fraction were not significantly different among the three land use practices, changes in chemically-protected carbon showed that there were more decomposed organic material in soils under arable cropping and native vegetation than those under forest. However, relative proportion of the various carbon fractions showed that protection occurred mostly in the 0-5cm depth.

CONCLUSION

Land use practices (such as forestation and natural fallow) that mimic the natural system that previously exist in ecology would favor improved soil structural stability as indicated by increase MWD and aggregate structure. Such improvement restore the ecosystem 'health' and makes it more functional to provide benefit like SOM build-up, protection from wind and water erosion and; retention and filtration of water amongst others. In dry land ecologies where desertification is a major form of land degradation, establishing forests could be an important strategy to rehabilitating degraded ecosystems.

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