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Soil Carbon Dynamics and Soil Properties Influenced by Different Types of Agronomic Land Use in the Forest Zone of Nigeria

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Abstract: Assessment of soil carbon dynamics under different agronomic land use could inform soil management practice intervention. Relatively few studies have examined the effects of different agronomic land use beyond routine soil physico-chemical properties, let alone the effects on soil organic matter and critical soil organic matter (SOMc), a basic index of assessing soil degradation. A study was conducted from 2013to 2014 on Alfisols of the humid forest zone of Nigeria to assess soil characteristics under the different agronomic land use, namely; cocoa plantation, cassava farming, natural fallow land and mixed cropping. The aim was to determine accumulation of soil organic matter, some hydropysico-chemical properties and critical soil organic matter so as to reveal the stability of the soils and prescribe soil management strategies. Coefficient of variability (CV %) of the soil properties explained the influence of the land uses on soil properties. Soil characteristics, except sand and sand fractions; but characteristics such as bulk density, WSA, pH, Na and base saturation were not influenced by different types of agronomic land use. Based on the saturated hydraulic conductivity, the studied soil was categorized in very slow to slow conductivity class. Carbon accumulation in the soil varied among the different plantation types with an increasing order: Cocoa plantation > grassland > mixed cropping field > natural fallow > cassava farming. The SOC_C values revealed unstable soil structure in cocoa plantation, grassland and mixed cropping farm land and indicated the risk of soil degradation (SOC_C = 5–7 %) while cassava farmland was more prone to degradation as the soil suffer from loss of soil structure and is highly susceptible to erosion (SOC_C = < 5 %).

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1. Introduction

Alfisols in the forest zone of Nigeria occur on basalt and crystalline rocks and Ultisols are derived from granite, geneses and sands (Jungerius, 1975). These soils are referred to as low activity clay (LAC) soils (Juo, 1981). Low activity clay soils posse effective cation exchange capacity (ECEC) of less than 14 c mol kg^{-1} in the diagnostic horizon where the influence of organic matter is least. Based on the mineralogical and surface characteristics, Alfisols are referred to as Kaolinitic LAC soils. Under natural vegetation, the soil possesses favourable properties. This is mainly due to adequate supplies of soil organic matter (SOM) from falling litters and decay tree branches and the burrowing in and out of soil organisms and decay dead roots that open up the soil for improved porosity and infiltration of water. Some natural ecosystems have been replaced by crops, pastures, buildings or roads, while the remaining is often highly affected by human activities (Duiker, 2011). Like in other countries of the world, Nigeria possesses the similar condition. In the humid forest zone of Nigeria, mono-cropping system by small scale farmers is spreading rapidly at the cost of natural vegetation, thus disturbing natural ecosystem of the region.

Adequate presence of SOM is required for the aggregation of soil particles and improvement of soil hydropysico-chemical properties. According to Seedling (2009), ample supply of SOM in the soil ensures its strength against erosion, improves its chemical buffering capacity and water holding capacity and reduces chances of floods in case of excessive rainfall. Soil acidity and alkalinity also, fall progressively, reducing or eliminating the toxicity that has become a major problem in tropical soils. In addition, increased soil biological activity would protect plants against pest and diseases. With the removal of forest vegetation and conversion to smallholder fields and other land use, the once favourable soil physical, chemical and biological properties are easily lost because of the exposure to high temperature, high intensity tropical storm and unwise farming techniques.

Rapidly increasing population has forced agriculturists to explore ways to increase food production either by elevating crop yield per unit area or expanding the area under cultivation. According to Duiker (2011), there is still land available to take into production, but this land will be of progressively poorer quality for crop production. Eswran*et al*., (1999) considering global land availability for rain-fed crop production, reported that only 13 % of the land was prime or good, while majority of the rest lies in the marginal to very marginal (42 %) and unsuitable (45 %) for crop production. The researcher noted that the most prime and good land has already been in use and are sensitive to degradation and nutrient depletion. Special practices are required to make marginal lands suitable for crop cultivation, with minimum environmental reservations and with our compromising crop yield (Duke, 2011). Sustainable farming techniques are the right choice for this purpose, however, these are not widely practiced in Nigeria.

The capacity of the soil to support plant growth (good yield and quality) is determined by the physical, chemical and biological properties of the soil. Land degradation is manifesting in the form of depletion or decline in physical, chemical and biological properties of the soil. All soil properties are continuously influenced by land use at various levels of management, such as cropping system and the farming system (Dumanski*et al*., 1998; Braimoh *et al*., 2005). In addition, soil structure, amount of SOM, water and nutrient holding capacity are all affected by land use (Kosmas *et al*., 200; Lal, 1995; Shukla *et al*., 2003) and are of prime importance for crop production. For instance, SOM loss differs from land use type to another. Loss of SOM will therefore reduce soil fertility, degrade soil structure and water holding capacity and ultimately lead to land degradation (Lawal *et al*., 2009).

Present knowledge shows that land use is one of the drivers of the global carbon dynamics. In a study by Zhao et al., (2013), forest giving way to urban settlements was a major factor responsible for about 36 % reduction in carbon sequestration in Florida. Lawal *et al*., (2009) reported that good and appropriate land use practice has the ability to substantially increase potential carbon sink in soils. The stability of an agricultural soil is tied to SOM or humus. The amount of humus in the soil cannot be measured directly but is estimated by measuring the soil organic carbon (SOC) percentage and multiplying this by a conversion factor of 1.72 (Nelson and Sommers, 1982). Relatively few studies have ascertained carbon under different agronomic use types, particularly using IPCC standards of soil depth of 0 -30 cm and also, examined the effects of land use types on soil properties beyond particle size distribution, bulk density and routine soil chemical properties. Organic carbon could be described as “engine of the soil” and critical SOM content is an important index of assessing soil degradation that is rarely used. Identifying soil properties under land use types could be a veritable monitoring tool to guide decision on early intervention measures against soil degradation associated with land use types. The objective of this study was to evaluate how different agronomic land-use types impact on soil carbon.

2. Material and Methods

The study was conducted in Cross River State, Nigeria (Figure 1). The experimental location has a tropical climate with a rainy season starting from April to September, 2013 while the dry season extended from late October till March, 2014.. The rainfall pattern is bi- modal with peaks in June and September. The mean annual rainfall of the area ranged from 2,250 to 2,500 mm. The mean annual temperature is 29^{o} C (CRADP, 1992). The soil type is Alfisol. The study location is predominantly planted with Cocoa with patches of cassava farms, fallow lands, grasslands and mixed cropping. These five types of land use practices were used to investigate their impact on soil hydro, physical and chemical properties.

2.1 Field sampling

At each land use undisturbed core samples were collected at a depth of 0–30 cm from randomly selected positions using a cylindrical core of 30 cm length. The samples were bulked to get composite samples for each land use.

2.2 Chemical properties determination

Soil pH was determined (1:2.5 soil, water suspension) using the pH meter (IITA, 1982). Organic carbon was determined by the wet oxidation method (Nelson and Sommers, 1982). Total nitrogen was determined using the Micro-Kjeldahl method (Bremner and Mulvaney, 1982) while Bray P-I method was used to calculate available phosphorous (Olsen and Sommers, 1982), since the soils are not calcareous. Exchangeable bases (Ca, Mg, Na, and K) were extracted with 1 N NH_4OAc buffered at pH 7.0

(Thomas, 1982). Exchangeable acidity was determined by titration with 0.05 N NaOH while effective cation exchange capacity CEC was taken as the summation of exchangeable bases and total exchangeable acidity (IITA, 1982).

2.3 Physical properties determination

Core samples were collected for dry bulk density, porosity and macro aggregate stability analysis {Water Stable Aggregate (WSA)}. Particle size analysis was done using the hydrometer method (Gee and Bauder, 1986). Bulk density was determined by the core method (Burke *et al.* 1986). Porosity was calculated as the function of total volume not occupied by soil solid, assuming a particle density of 2.65 Mg m^{-3} (Danielson and Sutherland, 1986). Water stable aggregate at 0–30 cm soil depth was determined with air-dried samples. The aggregates were wet sieved using Yoder (1936) modified technique (Whitbread *et al.* 1996; Oku, 2004) using a set of graduated nest of sieves with pores of 4.75 mm, 2 mm, 1 mm and 0.25 mm. This was done by scooping a 50 g soil sample on the topmost of the nest of four sieves, immersing the sieves in water with rising and lowering the nest of 4.75 mm, 2 mm, 1 mm and 0.25 mm, through water 20 times. The stable aggregates on each sieve were washed into separate moisture cans. Each content of aggregate oven dried at 105 ºC to a constant weight (72 h). Correction for sand was done using sodium hydroxide (NaoH) as a dispersing agent. The percentage WSA was calculated as stipulated by Kemper and Rosenau (1986).

$$\% \text{ WSA} = \frac{\text{wt of soil retained on sieve} - \text{wt of sand}}{\text{Total sample wt} - \text{wt of sand}} \times \frac{100}{1}$$

Preliminary test was first conducted using 10, 20 and 30 cycles of lowering and rising in a 50 cm deep water pool. The breakdown of aggregates after 10, 20 and 30 cycles of lowering and rising in a pool of water for each soil was determined.

2.4 Carbon accumulation

Carbon accumulation was calculated using Schlesinger (1986) formula

Organic carbon accumulation (kg ha^{-1}) = carbon x bulk density x soil depth x 104

Where carbon in the soil is in g kg^{-1}, bulk density in Mg m^{-3}, and depth of soil is 0.30 m.

2.5 Data analysis

Variability in soil properties was estimated using coefficient of variation (CV). Properties with larger CV values are more variable than those with smaller CV values. Wilding (1985) had described a classification scheme for identifying the extent of variability in soil properties based on their CV values in which CV values of 0 – 15, 16 – 35 and > 36 % indicate little (least), moderate and high variability respectively.

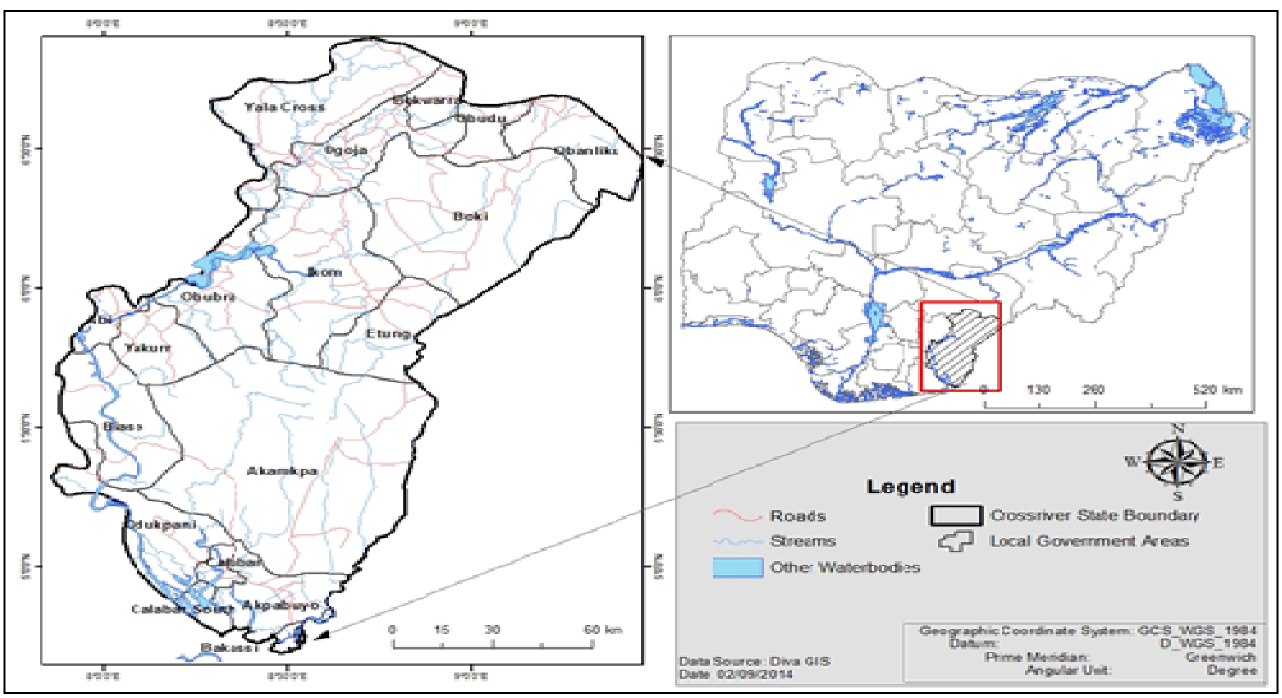

Figure 1. Map showing the study area in Nigeria, West Africa

3. Results and discussion

3.1 Physical properties

Particle size distribution (PSD)

The distribution of soil separates within the agronomic land use types studied is shown in Table 1. The PSD of the soil under the various agronomic land use indicated preponderance of sand indicating that the soil skeletal structure is coarse with restricted silt. This implies that the soils are easily detached by the agents of erosion, but the transportation of the particles will be low (Oku and Babalola, 2009). With these textures, the specific surface areas of the soil are small. This means the soil will possess low cation exchange capacity with little ability to retain plant nutrients as cation exchange sites are limited (Oku and Edicha, 2009). This again accounts for the low native fertility of the soil.

Bulk density and porosity

Bulk density ranged from 1.34 – 1.48 g cm^{-3}. The bulk density of the soil is directly related to the porosity of the soil. The lower the bulk density, the higher the porosity value, and the higher the rating of the soil for crop production. Increase in porosity was in the following order; cocoa plantation > grassland > fallow land > cassava farmland > mixed farming plot. The porosity values put the soil under cocoa plantation, grassland and mixed cropping into a "satisfactory agricultural soil". Whereas, the porosity value of 47 and 49 % obtained for natural fallow land and cassava farmland respectively puts the soil into a class of "good agricultural soil" (46 – 50 %) (Kachinskii, 1970; Oku and Edicha, 2009). To increase the porosity of tropical soil, Kachinskii (1970), recommended intensive tillage of the soil.

Soil carbon accumulation and stability

Table 3 shows, carbon accumulation under the different land use types. The accumulation was in the order of cocoa plantation > grassland > mixed cropping farm > natural forest > cassava farm. The comparative higher accumulation of soil carbon in a cocoa plantation followed by grassland and mixed cropping fields is expected. This is because the soil under this land use, particularly cocoa has higher decomposed materials of plant, microbial and animal origin (Post and Kwon, 2000). Regular monitoring of soil carbon build-up or depleting, could help in early detection and arrest of soil degradation and deterioration in soil physical health. Soil carbon impacts positively on the stability of soils. Water stable aggregates (Table 1) showed that water stable aggregates under cocoa plantation and grassland were more stable than for cassava farm land, fallow land and mixed cropping farm. Soil organic matter (SOM) concentration plays a major role in the forming and stabilization of aggregates.

The critical SOM (SOM_C) values revealed that cocoa plantation, grassland and mixed cropping farm land possessed unstable structure and stand the risk of soil degradation (SOM_C = 5–7 %) while cassava farmland was more critical as the soil suffer from loss of soil structure and is highly susceptible to erosion (S =< 5 %) (Pierie, 1991). The loss in structure of the soil under natural fallow land indicated that the soil had not yet recovered as at the time of the study (land use factor < 5). A land use factor of < 5 is associated with serious erosion and declining soil productivity (Armon, 1984).

Table 1. Soil physical properties as influenced by different agronomic land use

Parameters	Cocoa plantation	Cassava farmland	Grass land	Fallow land	Mixed cropping farmland	CV (%)
Coarse sand (g kg^{-1})	461	393	521	491	546	12
Very fine sand (g kg^{-1})	88	56	48	77	63	24
Silt (g kg^{-1})	250	210	250	240	230	7
Clay (g kg^{-1})	201	341	181	261	161	31
Texture	scl	cl	sl	scl	sl	
Bulk density (g cm^{-3})	1.44	1.34	1.46	1.39	1.48	4
Porosity (%)	45	49	45	47	44	4
Water stable aggregates (%)	31.4	29.3	31.2	29.6	30.3	3
Critical SOM (%)	7.5	4	7.6	4.6	6.9	27
Saturated Hydraulic conductivity (cm hr^{-1})	0.70	0.23	0.94	0.42	1.18	55

scl = sandy clay loam, cl = clay loam, sl = sandy loam, CV= coefficient of variability

The soil here, if allow to recover its fertility through natural fallow will take longer time (years) to recover. This is so as the soil has lost its structure, and the natural recovery process here is often interrupted by annual indiscriminate bush burning. The recovery process could be fast-tracked with the deliberate introduction of soil fertility enhancing trees as multi-purpose tree (MPT) species and also with a ban placed on indiscriminate bush burning by the community council of Chiefs.

3.2 Physico-hydrological properties

Some physico-hydrological properties are presented in Table 1 above. The saturated hydraulic conductivity of the soils under the various agronomic land uses were in the slow class (< 0.8 cm hr-1) except for the soil under mixed cropping that fell under the slow conductivity class (0.8 - 8 2 cmhr^{-1}). This implies the soils are prone to erosion under heavy downpour. This is collaborated with the critical SOM index (S_1)

3.3 Chemical properties

Table 2 below, shows the soil chemical environment of the studied location as influenced by the different agronomic land use. The pH under cocoa plantation, natural fallow land and mixed cropping farm land are rated as moderately acidic while the pH under cassava farm land and grassland are rated as strongly acidic. The rating of the soil into 2 classes despite the low variability (CV) of soil pH among the land use is indicative that the expected rates of acidification vary between land use and such rates could be increased by the high annual rainfall characteristics of the studied location and high removal of biomass and plant materials from the soil. The soil organic carbon (SOC) and SOM content followed the same trend as that of the pH. In soil fertility rating SOC and SOM were rated as moderate under cocoa plantation, grassland and mixed cropping farm land whereas this was rated as low under cassava farm land and fallow land. The low SOC content among the land use had earlier been explained.

Available phosphorus levels among the land uses were rated as very low for the studied land uses except under mixed cropping farm land that was rated as low. However, these very low and low fertility ratings of available phosphorus are expected as the soil is acidic (low pH values) hence the reduction in phosphorus availability. The sodium content of the soil was rated as low (0.1–0.3 c mol kg^{-1}) in all the land uses. Potassium level was rated as very low (< 0.2 c mol kg^{-1}) in all the studied land uses. Calcium was rated as medium (5.5–10 c mol kg^{-1}) under cocoa plantation whereas it was rated as low (2–5 c mol kg^{-1}) under cassava farm land, grass land, fallow land and mixed cropping farm land. The moderate level of calcium in soil sustaining cocoa could be attributed to the practice in the study location whereby the cocoa pod is cut open and the beans are taken home, leaving the empty pods on the field as manure to decompose. The Ca/Mg ratio indicated low Ca (1-4) (Eckert, 1987). From soil chemistry point, calcium deficiencies as observed in the studied soil are only found in very acidic soils.

Table 2. Soil chemical properties as influenced by different agronomic land use

Parameters	Cocoa plantation	Cassava farmland	Grass land	Fallow land	Mixed cropping	CV (%)
pH (2.5:1 water: soil)	5.20	5.10	5.10	5.40	5.20	2
Nitrogen (g kg^{-1})	0.15	0.10	0.15	0.11	0.11	19
Organic carbon (g kg^{-1})	1.95	1.26	1.89	1.34	1.57	19
Organic matter (g kg^{-1})	7.47	4.02	7.58	4.62	6.94	27
Phosphorus (mg kg^{-1})	3.90	3.30	3.00	3.10	7.10	42
Sodium (c mol kg^{-1})	0.12	0.10	0.11	0.10	0.11	8
Potassium (c mol kg^{-1})	0.17	0.11	0.14	0.13	0.15	16
Calcium (c mol kg^{-1})	9.80	2.60	4.00	3.60	3.46	62
Magnesium (c mol kg^{-1})	4.00	2.60	1.80	2.00	3.80	36
Exchangeable acidity (c mol kg^{-1})	0.84	1.20	1.08	0.92	1.36	19
ECEC (c mol kg^{-1})	14.90	6,60	7.10	6.80	10.00	40
Base saturation (g kg^{-1})	94	82	85	86	86	5
Ca/Mg ratio	2.5	1	2.2	1.8	1.2	37

CV= coefficient of variability

Magnesium level was rated high (3–8 c mol kg^{-1}) for cocoa plantation and mixed cropping farm land, whereas the levels were moderate (1–3 c mol kg-1) under cassava farm land, grassland and fallow land. The high and moderate level of magnesium combined with sodium is implicated in dispersion of the soil and this is collaborated in the structural loss and proneness of the soils to degradation. The effective cation exchange capacity (ECEC) level under cocoa plantation and mixed cropping farm land was moderate (8–15 c mol kg^{-1}) whereas it was low (< 8 c mol kg^{-1}) for soils under cassava farm land, grassland and fallow land (Udo and Ogunwale, 1986; Holland *et al*., 1989). The base saturation (BS) percent of the soil under the various land use were very high (> 80%) indicating how closely nutrient status approaches potential fertility. Theoretically, this level of BS indicates that the soil sustaining the various agronomic land use is weakly leached but on the contrary the pH is low (acidic and moderately acidic)

Soil variability among agronomic land use

The influence of agronomic land use types on soil properties are shown in Table 1 and 2. The coarse sand and silt fraction, bulk density, porosity and WSA were least variable (CV < 15 %. Whereas very fine sand (vfs) and clay fractions, and critical SOM were moderately variable (CV = 16 – 35 %). Only SHC in this study was highly variable (CV > 35 %) (Oguike and Mbagwu, 2009; Igwe*et al*., 1999).. Variability in soil pH, sodium and base saturation were low (Ogunkunle, 1993; Mulla and McBratney, 2001: Oku *et al*., 2009). The low variability among the various land use is indicative that land use does not affect these soil properties.

The coefficient of variability (CV) of nitrogen, soil organic carbon, soil organic matter, potassium, and exchangeable acidity were between 16 – 35 %. Variability in magnesium, phosphorus, calcium, ECEC, and Ca/Mg ratio were high (CV > 35 %). The result indicates that agronomic land use types imposed influence on soil properties as vfs, clay fractions, critical SOM, SHC, N organic carbon, soil organic matter, phosphorus, potassium, calcium, magnesium, exchangeable acidity and Ca/Mg ratio. Contrary to reports by Dumanski*et al*., 1998; Tan et al., 2003; Braimoh*et al*., 2000 that, all soil properties are continuously influenced by land use at various levels of management and cropping system, coarse sand and silt fractions, bulk density and porosity, soil pH, sodium, and base saturation were not affected by land use. This means the same soil management strategy aims at upgrading these physical chemical properties could be applied to all the studied agronomic land use. Variation in carbon accumulation was at the boundary of transiting from least to moderate variability. The moderate and high variability in most soil properties is indicative that, no one soil management strategy will fit all the land use types.

Table 3. Carbon accumulation in the soil as influenced by different agronomic land use types.

land use types	Soil Carbon accumulation (t ha^{-1})
Cocoa plantation	6.12
Cassava farmland	4.42
Grassland	6.07
Natural fallow	4.62
Mixed cropping farmland	5.84
CV %	15

CV= coefficient of variability

Soils management strategies

The management strategies prescribed here are based on the soil physico-chemical properties obtained. Recommended tillage practice for tropical soil would accelerate erosion if employed for the studied soil. Porosity of the soil could still be improved with mulching. Mulching will create favourable micro environment for soil ecological engineers to inhabit the soil thereby improving its porosity. Variability occurred in soil properties among the different land use indicating that different soil management strategies should not be adopted, but the soils were generally deficient in the major plant nutrients.

For sustainable continuous cultivation and sustenance of soil health, conscious effort must be made to increase organic matter (OM) in the soil under the various land use to raise their rating to high. This is required, given the high temperature and rainfall pattern of the study location. The benefits of OM to the soil are multiple and tremendous; having a great positive influence on the physical and chemical properties of the soils.

This will promote the stability of the soil aggregates, thereby improving the structure of the soil. Also, soil consistence (workability) and soil microbiological properties are improved by SOM (Kparmwang, 2008). Chemically, OM supplies nutrients like N, P and S as well as micronutrient elements such as B, Cu, Mo, Zn, Mn, Cl. The OM also serves as a binding agent of soil particles into aggregates. This promotes the development of good soil structure. The humus component of SOM increases the CEC of the soil. It is better not to lime the studied soils since they have low exchangeable acidity. Adequate OM will improve the soil pH and buffering capacity.

Apart from the cocoa plantation, other farm lands (agronomic land use) studied were small-holder close distant fields, therefore the sources of OM are farmyard manure, and domestic animal wastes. These were of mixed sources due to the diversified mixture of domestic animals and household wastes. Return of crop residues to the field after crop harvest should be the practice. The soils under all the different agronomic land use types are deficit in the macro nutrients N, P and K and would, therefore, require NPK fertilizers. It is recommended that the NPK fertilizer be combined with organo-mineral fertilizer, which is often high OM. This will also, increase carbon accumulation and improve soil aggregate stability and water retention against the climate change crisis.

4. Conclusion

For the Alfisols of the humid forest zone of Nigeria, the agronomic land use type imposed on the soil influenced most of the soil properties assessed. Carbon accumulation was highest in soils under cocoa plantation followed by grassland soils and was lowest in cassava crop sustaining soil. Critical SOM revealed that all the soil under the different agronomic land uses possessed unstable structures and stand the risk of soil degradation. Also the natural fallow land under this study had lost its structure and will need many more years to attain equilibrium or fully recover from its over exploitation. All the agronomic land use types will require high external input in the form of heavy dosage of organic manure bulked with NPK fertilizer to improve fertility and productivity and keep the land under cultivation, in order to alleviate poverty.

Competing Interests

Authors declare that they have no competing interests.

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