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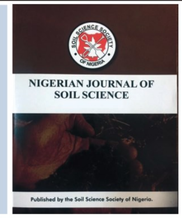

Soil organic carbon fractions and aggregation of a tropical Alfisol as affected by plant residues

Adesodun J. K.[1], Udom B. E.[2], Abudu O. S.[1], Adejuyigbe C. O.[1], Enikuomehin O. A.[3], Thannia B. M.[1] , Oke O. O.[1] , Olowokere F. A.[1], Oyegoke C. O.[1], Mbila M.[4], A. A.[1] Olubode A. A.[1]

1. *Department of Soil Science and Land Management, Federal University of Agriculture, P. M. B. 2240, Abeokuta 110001, Ogun-State, Nigeria*
2. *Department of Crop and Soil Science, Faculty of Agriculture, University of Port Harcourt, P.M.B. 5323, Port Harcourt, Nigeria*
3. *Department of Crop Protection, Federal University of Agriculture, P. M. B. 2240, Abeokuta 110001, Ogun-State, Nigeria*
4. *Department of Biological and Environmental Sciences, Alabama Agricultural and Mechanical University, 4900 Meridian Street North, Normal, Alabama 35762, USA*

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Corresponding Author's E-mail Address:

ebassidy@yahoo.com +23478035402352

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ABSTRACT

Incorporation of plant residues into soil plays vital role in enhancing quality of fragile tropical soils. This study evaluated short-term effect of plant residues of different quality on organic carbon (OC) fractions, carbon management indices and stability of a sandy loam soil with low (< 2%) initial OC content. The residues are Banana clippings (BC), *Chromolaena odorata* (CO), *Leucaena leucocephala* (LL), Maize Stover (MS), Neem clippings (NC), and *Panicum maximum* (PM) applied at 0 t ha^{-1} (control), 10 t ha^{-1} and 20 t ha^{-1}. These treatments were arranged in a randomized complete block design and replicated three times. Undisturbed soil samples were collected at 0-20 cm depth for determination of percent water stable aggregates (%WSA), aggregate ratio (AR) and Mean Weight Diameter (MWD). Pre-sieved (2 mm) soil samples from same depth were collected to determine structural index (SI), microaggregate stability, total OC (C_T), labile OC (C_L) and non-labile OC (C_{NL}). Carbon indices, i.e. lability index (LI), carbon management index (CMI) and carbon pool index (CPI) were computed from the OC fractions to evaluate the best management practice. The OC fractions were significantly ($p \leq 0.05$) higher with LL applied at 20 t ha^{-1} (19.29 g kg^{-1} for C_T, 1.20 g kg^{-1} for C_L and 18.09 g kg^{-1} for C_{NL}) than other treatments. This was followed by PM 10 t ha^{-1}, with 17.16 g kg^{-1} for C_T and 16.44 g kg^{-1} for C_{NL}. The LI (1.29) was highest with MS 10 t ha^{-1}, while CMI (166.6) and CPI (1.85) were highest with LL 10 t ha^{-1} and 20 t ha^{-1} respectively. Significant increase in %WSA of > 0.25 mm size over < 0.25 mm was observed with addition of residues which indicates binding of smaller aggregates into large fractions; while AR (11.97) was highest with CO 10 t ha^{-1}. Aggregate stability showed MWD (2.02 mm) was highest in soils treated with CO followed by PM (MWD = 1.86 mm) both at 20 t ha^{-1}; but SI trend was higher with addition of LL and PM. Computed micro-aggregate stability indices were generally similar for all treatments. High positive correlations were obtained between MWD and C_L (r = 0.634), LI (r = 0.686) and CMI (r = 0.641) with addition of *Leucaena leucocephala.* In conclusion, L. *leucocephala,* followed by P. *maximum* and C. *odorata* provided short-term improvement in physical quality of this soil over other plant residues.

1.0. Introduction

Agriculture faces significant challenges in meeting food production (Stevenson *et al*., 2013); and in recent years, challenges in sustainable food production was partly due to climate change. A double share of the problem is faced especially in sub-Sahara Africa where most of the soils are inherently infertile and are continuously exposed to more harsh climatic weather condition which in turn exacerbates the problem. Hence, adoption of management practices to ameliorate these problems becomes very necessary.

Environmental quality and soil productivity depend on several related soil physical properties such as soil aggregation and stability, soil density, water holding capacity, infiltration, and aeration; and these properties are impacted to varying degrees by management practices including residue, manure application and cropping system practices. Therefore, application of organic materials as soil amendments were reported to be an important management strategy that can improve soil quality characteristics and alter the nutrient cycling through mineralization or immobilization turnover of added materials (Campos *et al*., 2013; Baldi and Toselli, 2014; Novara *et al*., 2013; Hueso-González *et al*., 2014; Oliveira *et al*., 2014).

Majority of the smallholder farmers in Nigeria usually incorporate residues derived from plants into their croplands in a bid to improve fertility and productivity of nutrient poor soils, and also help reduce the cost spent on fertilizer. As type and nature of plant residues influence the rate of decomposition and type of nutrient release, Awodun and Ojeniyi (1999) noted that type of residue incorporation also determines its impact on soil properties as well as crop yield due to difference in biochemical quality of plant mulch material. Hence, it is necessary to document the potentials of different plant residues readily found in some tropical environments to improve soil quality. However, Parwada and Van Tol (2018) stated that the resilience of soils under varying residue quality, assessed by CN ratio, is unclear. Plant material with a low CN ratio is classed as high quality; whereas, those with higher CN ratio was noted by Parwada and Tol (2018) to be of low quality.

Accumulation of carbon (C) in soils is a function of relationship between C-inputs in the form of crop residues and organic fertilizers, soil type and temperature (Li *et al*., 2018; Cooper *et al*., 2011) and rate of residue decomposition. While Blair *et al.* (1995) noted soil carbon (C) as a major determinant of sustainable agricultural system, Adesodun *et al*. (2007) observed that the decline in organic matter content of most tropical soils is responsible for major reason of their high degradation. Blair *et al.,* (1995) also stated that why sustained productivity of agricultural systems is the maintenance of the soil organic matter (SOM) levels, they further reported that small changes in total SOM or C are difficult to detect because of natural soil variability. Hence there is need to use labile organic C fraction which is a more sensitive indicator to assess changes in soil quality. The labile organic C is a small proportion of total organic carbon. It includes microbial biomass C, dissolved organic C, particulate organic C and potassium permanganate-oxidizable C (Mi *et al*., 2016; Haynes, 2005). This study therefore evaluated short-time improvement in the concentration of organic carbon (OC) fractions and their relationship to stability of a tropical soil exposed to frequent high risk of water erosion following the application of plant residues of different qualities.

2. Materials and methods

2.1. Experimental site

The site selected for the field experiment was in the Organic Farm of Federal University of Agriculture, Abeokuta, Ogun State, Nigeria (Latitude 7.12° N and Longitude 3.23° E). This area is located within the transition zone of the sub-humid forest to the south and the derived savannah to the northwest. The soil at this site is well-drained sandy loam on the surface with gravelly sandy clay loam in the subsurface derived from the basement complex; and classifies as an Oxic Paleustalf (FDALR, 1990). Selected physical and chemical properties of this site are shown in Table 1.

Table 1. Some physical and chemical properties of the soil

Soil properties	Units	Values
Sand	%	86.2
Silt	%	12.0
Clay	%	1.8
Texture	-	Sandy loam
pH	-	6.2
Organic carbon	%	1.12
Total N	%	0.18
C:N	-	6.2
Available P	Mg kg^{-1}	22.4
Exch. K	C mol kg^{-1}	0.08
Exch. Na	C mol kg^{-1}	0.32
Exch. Ca	C mol kg^{-1}	1.25
Exch. Mg	C mol kg^{-1}	2.5
Exch. Acidity	C mol kg^{-1}	2.6
ECEC	C mol kg^{-1}	6.65

ECEC- Effective cation exchange capacity

The site is characterized by bimodal rainfall distribution with distinct wet season from April to October and dry season from November to February. This area has a relatively undulating topography, and the mean annual rainfall is about 1400 mm with maximum in July. The mean monthly temperature range varies between 28 °C and 32 °C.

2.2. Experimental treatment and land preparation

The experiment which was conducted in the planting season of the year 2013 was laid out in a randomized complete block design (RCBD). Six (6) plant materials, i.e. *Chromolaena odorata*, Neem Clippings, Banana Clippings, *Panicum maximum*, Maize Stover and *Leuceana leucocephala* were uniformly applied and incorporated into the experimental plots as residues at 0 t/ha (control), 10 t/ha and 20 t/ha; and were replicated three times to make a total of fifty four (54) plots. These plant materials which are readily available at the beginning of cropping season in the area were collected and dried, while maize Stover were collected and stored from previous harvest. The control was used as the reference. Land for this experiment with a total area of 44 m by 29 m (1276 m^2) was manually cleared, pegged and demarcated into 4 m × 4 m while the inter and intra plot spacing was 1 m each. Maize (*Zea may* L) variety TZEE 1-Y (early maturing) was planted two weeks after incorporation of plant residues as test crop (data not presented). Prior to the application of residues, soil samples were collected randomly across the field with the aid of soil auger at 0–20 cm depth. The soil samples were mixed to obtain a composite sample which was air dried, passed through 2 mm sieve and analysed for some physical and chemical properties shown in Table 1. Triplicate samples of each plant residue before incorporation into the plots were washed with running tap water, dried at 65 ^{o}C in oven for 48 hours, milled into size of 0.5 cm and analysed by standard procedures for chemical concentrations presented in Table 2.

Table 2. Some properties of the plant residues incorporated to the soils

Plant Residue	OC	TN	C;N	Av. P	K	Na	Ca	Mg	C
	(%)	(%)		(mg kg^{-1})	mol kg^{-1}				
Chromolena odorata	8.72	1.13	7.72	32.4	0.33	0.63		0.42	0.63
Maize stover	7.76	1.05	7.4	29.45	0.27	0.57		0.36	0.46
Neem clippngs	9.73	1.03	9.45	34.5	0.27	0.95		0.40	0.74
Leucena leucocephala	9.65	1.99	4.85	37.4	0.26	0.86		0.52	0.74
Panicum maximum	9.60	1.28	7.50	41.8	0.27	0.86		0.42	0.69
Banana clippings	9.02	1.11	8.13	39.1	0.36	0.8		0.42	0.63

2.3. Determination of total and carbon fractions, and their derivations

Soil samples were collected at harvest from 0-20 cm depth across all plots, while control samples were the reference. All samples were air dried at room temperature, slightly crushed and sieved to < 2 mm; while subsamples were taken and ground to 0.5 mm for determination of organic carbon (OC) concentration. Total organic carbon (C_T) was determined using acid dichromate wet-oxidation procedure of Walkley and Black (1934) as adapted by Nelson and Sommers (1996). Carbon fractionation into labile (C_L) and non-labile OC (C_{NL}) were determined according to potassium permanganate ($KMnO_4$) oxidation technique called Weil Carbon (Weil *et al.*, 2003) as outlined by Culman *et al.* (2014). Blair *et al.* (1995) described active carbon or labile carbon (C_L) as the amount of carbon oxidized by $KMnO_4$ in a soil sample and non-labile carbon (C_{NL}) to be equal to total carbon (C_T) minus labile carbon (C_L), i.e. $C_{NL} = C_T - C_L$.

In this work, 5 g sample of soils pre-sieved with < 2 mm from each subplot were oxidized with 0.02M $KMnO_4$ diluted with distilled water. Samples were shaken for 2 minutes and allowed to stand undisturbed for 10 minutes. A small aliquot of the supernatants were diluted with distilled water and the absorbance of the solution was read at 550 nm using a UV spectrophotometer. Extractable carbon, i.e. C_L by 0.02M $KMnO_4$ was reported as mg C kg^{-1} soil. Carbon indices, i.e. carbon pool index (CPI), Lability index (LI) and carbon management index (CMI) were calculated using the procedure of Blair *et al.,* (1995) where control treatment was the reference as:

$$\text{Lability of C} = C_L / C_{NL} \quad (1)$$

$$\text{CPI} = C_T \text{ sample (g kg}^{-1}) / C_T \text{ reference (g kg}^{-1}) \quad (2)$$

$$\text{LI} = \text{Lability of C in sample soil/Lability of C in reference soil} \quad (3)$$

$$\text{CMI} = \text{CPI} \times \text{LI} \times 100 \quad (4)$$

where, sample refers to soil from amended plots.

Demisie *et al.* (2014) reported higher CPI (CPI > 1) or lower (CPI < 1) to indicate higher OC accumulation or loss respectively. They further stated that higher LI (LI > 1) and lower LI (LI < 1) represents higher and less labile OC content due to decomposition of organic matter respectively. According to Chatterjee *et al.* (2018), CMI which provides a sensitive measure of the rate of change in soil C dynamics relative to a reference soil has no 'ideal' value. However, CMI indicates if the system is being rehabilitated or in decline over time or when a new practice is introduced (Chatterjee *et al.*, 2018).Whereas, Demisie *et al.* (2014) expressed CMI to be higher (CMI > 100) and lower (CMI < 100) when compared with a reference arbitrarily chosen as 100 to indicate increase or decrease in soil quality respectively.

2.4. Aggregate size distribution and stability indices

Aggregate size distribution was measured by wet-sieve method as described by Kemper and Rosenau (1986). In this procedure, 50 g of the < 5.66 mm aggregates were placed on the topmost of a nest of sieve of diameters 2, 1, 0.5 and 0.25 mm. The samples were pre-soaked in distilled water for 10 min before oscillating vertically in water 20 times (along 5 cm amplitude) at the rate of 15 stokes mm^{-1} for 2 min. The resultant aggregates on each sieve were dried at 105 °C for 24 hours and weighed; while the mass of < 0.25 mm fraction was obtained by difference between the initial sample weight and the sum of sample weights collected on the > 0.25 mm nest of sieves.

The percent water stable aggregates (%WSA) on each of the following size ranges, 5.66-2.0, 2.0-1.0, 1.0-0.50, 0.50-0.25 and < 0.25 mm were obtained as:

$$\%WSA = (M_{a+s} - M_s/M_t - M_s) \times 100 \quad (5)$$

Where M_{a+s} is the mass of the resistant aggregates plus stone (g), M_s is the mass of the stone fraction alone, and M_t is the total mass of the sieved soil (g).

The mean weight diameter (MWD) of wet-stable aggregates was calculate as

$$MWD = \sum_{i=1}^{n} XiWi \quad (6)$$

where, X_i is the mean diameter of each size fraction (mm),W_i is the proportion of the total sample weight (WSA) in the corresponding size fraction after deducting the weight of stone and n is the number of size fractions. Higher values of MWD indicate the dominance of the less erodible large aggregates of the soil (Adesodun *et al.*, 2007; Piccolo *et al.*, 1997).

Aggregate ratio (AR) was calculated according to Singh and Benbi (2018) as

$$AR = \frac{\%\ water\ stable\ macroaggregates>0.25\ mm}{\%\ water\ stable\ aggregates<0.25\ mm} \quad (7)$$

Soil stability was also assessed using the structural stability index (SI) defined by Pieri (1992) as:

$$SI = [1.72\ OC\%\ (wt)/\ (\%\ clay + silt)]\ 100 \quad (8)$$

where, SI ≤ 5% = structural degraded soil due to extensive loss of OC; SI 5-7% = high risk of structural degradation; SI 7-9% = low risk of soil structural degradation, i.e. relatively stable; and SI > 9% = sufficient OC to maintain structural stability, i.e. stable category.

Micro-aggregate stability was evaluated using particle size data obtained by hydrometer method as described by Gee and Bauder (1986). Thus, two 50 g of soil samples (< 2 mm pre-sieved) from each plot were used to determine the particle size distribution differently with sodium hexametaphosphate (Calgon) and distilled water as dispersants. The silt and clay values obtained from Calgon solution are termed as total silt and clay, while silt and clay values from distilled water are water-dispersible silt and clay. From these, soil micro-aggregate stability indices were calculated as follow:

Dispersion ratio (DR) = [(WDS + WDC) / (TSilt + TC)] (9)

Clay Dispersion Ratio (CDR) = WDC/TC (10)

Clay flocculation index (CFI) = [(TC – WDC)/TC (11)

Aggregate Silt + Clay (ASC) = (TC + TSilt) – (WDC + WDSilt) (12)

where, WDC is the water dispersible clay; WDS is the water dispersible silt; TC is the total clay and TS is the total silt. Higher value of DR and CDR means greater ability of soil to disperse (Igwe and Nwakocha, 2006), while higher values of CFI and ASC indicate better soil aggregation.

2.5. Data analysis

Data collected were analysed by general analysis of variance using the procedure of GenStat Release 9.2 (2007); while means were separated by Fisher least significant difference (LSD) at 5% probability level. Correlation analysis was used to determine the relationship of soil carbon fractions and the aggregate parameters.

3. Results and discussion

3.1. Soil properties and plant residue chemical composition

The soil of the study area was slightly acidic with low organic carbon (Table 1). The total nitrogen and available phosphorus were medium with values 0.18% and 22.40 mg/kg respectively. The different plant materials used also varied in their nutritional compositions (Table 2). Values obtained for organic carbon in all plant materials ranged from a minimum of 7.76% to the maximum of 9.73% as seen in Neem Clippings; while total nitrogen contents were higher in *Leucaena leucocephala* (1.99%) and *Panicum maximum* (1.28%) when compared to other plant materials used for the study. The results support the findings of Kononova (1961) who reported that organic residues from different genus are different in their biochemistry.

3.2. Soil organic carbon as mediated by incorporated plant residues

Total organic carbon (C_T) and non-labile organic carbon (C_{NL}) were generally increased (Table 3) in plots where plant residues were incorporated when compared to non-residue treatment (control) of this tropical soil with inherently low organic carbon (Table 1). Whereas, labile (C_L) OC increased over the control in plots treated with *Leucaena leucocephala, Chromolaena odorata* and Neem Clippings applied at 20 tons/ha, and Maize Stover (Table 3). These fractions of OC also varied significantly ($p \leq 0.05$) across plant residue treated plots in reference to the control. Application of *Leucaena leucocephala* at 20 tons/ha significantly ($p \leq 0.05$) had highest concentrations of the OC fractions; *viz*. C_T (19.29 g kg^{-1}), C_L (1.20 g kg^{-1}) and C_{NL} (18.09 g kg^{-1}). This was followed by *Panicum maximum* at 10 t ha^{-1} with 17.16 g kg^{-1} and 16.44 g kg^{-1} for C_T and C_{NL} concentrations respectively. Other significant ($p \leq 0.05$) increase in OC fractions over the control with plant residues treatment were observed with *Leucaena leucocephala* at 10 t ha^{-1} (17.02 g kg^{-1}) being > Maize Stover at 20 t ha^{-1} (16.49 g kg^{-1}) > *Chromolaena odorata* 20 t ha^{-1} (16.23 g kg^{-1}) > *Chromolaena odorata* at 10 t ha^{-1} (15.69 g kg^{-1}) for C_T; Maize Stover, *Chromolaena odorata* and Neem Clippings both at 20 t ha^{-1} (0.96 g kg^{-1}) for labile OC (C_L); and *Chromolaena odorata* (15.27 g kg^{-1}) and Maize Stover (15.77 g kg^{-1}) at 20 t ha^{-1}, and *Leucaena leucocephala* (16.31 g kg^{-1}) at 10 t ha^{-1} (Table 3). These results indicate separated forms of C accumulation in this soil, depending on the kind of plant residue over the control; and the observed trend was similar to the CN ratio of the plant residues reported in Table 2. The CN ratio was reported by Parwada and Tol (2018) as an indicator of residue quality, and that litter materials with a low CN ratio decomposes faster that those with higher C/N which indicates low quality. Hence application of *Leucaena leucocephala* with least CN (4.85) ratio presented in Table 2 led to highest concentrations of soil organic carbon obtained in the study. This observation was followed by *Panicum maximum* (CN = 7.50), Maize Stove (CN = 7.40) and *Chromolaena odorata* (CN = 7.72).

Table 3. Organic carbon fractions relative to plant residues incorporated

Treatment	Rate (t ha^{-1})	C_T (g kg^{-1})	C_L (g kg^{-1})	C_{NL} (g kg^{-1})
Control	0	10.37^{c}	0.7195^{c}	9.65^{c}
BC	10	12.90^{bc}	0.7191^{c}	12.18^{bc}
	20	14.76^{abc}	0.7191^{c}	14.04^{abc}
CO	10	15.69^{ab}	0.7195^{c}	14.97^{ab}
	20	16.23^{ab}	0.959^{ab}	15.27^{ab}
LL	10	17.02^{ab}	0.7189^{c}	16.31^{ab}
	20	19.29^{a}	1.196^{a}	18.09^{a}
MS	10	12.77^{bc}	0.1978^{ab}	11.81^{bc}
	20	16.49^{ab}	0.958^{ab}	15.53^{ab}
NC	10	14.76^{abc}	0.7192^{c}	14.04^{abc}
	20	14.50^{abc}	0.9588^{ab}	13.54^{abc}
PM	10	17.16^{ab}	0.7196^{c}	16.44^{ab}
	20	14.90^{abc}	0.7192^{c}	14.18^{abc}

CT - Total Carbon; CL- Labile Carbon; CNL- Non-Labile Carbon; BC- Banana Clipping
CO- Chromolaena odorata; LL- Leucaena leucocephala; MS- Maize Stover; NC- Neem Clippings; PM- Panicum maximum.
Values in columns for the same parameters with different letters indicate significant difference at $p \leq 0.05$.

3.3. Computed carbon indices

Carbon management indices *viz.* carbon pool index (CPI), labile index (LI) and carbon management index (CPI) are sensitive factors to assess change in soil management practices; and are used as rapid tool in evaluating change in soil quality. Generally, treatment with the plant residues significantly ($p \leq 0.05$) increased CPI which ranged between 1.24 and 1.85 over the control value 1.00 (Table 4); indicating higher accumulation of organic C with addition of the residues. Addition of *Leucaena leucocephala* at 20 tons/ha resulted in 85% increase in CPI over control, which was followed by 66% and 65% increase in CPI in plots amended with *Panicum maximum* at 10 t/ha and *Leucaena leucocephala* at 10 t/ha respectively. Compared with the control, LI increased with addition of Maize Stover 10 t ha^{-1} by 29% and Neem clippings 20 t ha^{-1} by 1% (Table 4). Results from this study also revealed that CMI (Table 4) was significantly ($p \leq 0.05$) affected by incorporation of some of the plant materials with reference to control which arbitrarily has a CMI of 100. The order of improvement in CMI was: *Leucaena leucocephala* at 20 t ha^{-1} (166.6) > Maize Stover > Neem clippings at 20 t ha^{-1} (134.8) > *Chromolaena odorata* at 20 t ha^{-1}. The CMI was lower majorly in plots that received *Panicum maximum*, Banana clippings and lower rate of 10 t ha^{-1} *Chromolaena odorata*, Neem clippings and *Leucaena leucocephala*. This observation corroborates with the findings of Blair *et al.* (1995) that reported increment in CMI under wheat cropping system with plant residue inclusion; and that of Mi *et al.* (2016) who reported higher CMI in soils treated with organic mulching materials than in chemical fertilizer treatment alone. Demisie *et al.* (2014) noted that CMI expresses soil quality in terms of increments on the total C content and in the proportion of labile C fraction; while Mi *et al.* (2016) and Blair *et al.* (1995) stated that actual CMI values were not important but the differences in this index reflect how management practices affected the reference used. However, Chaudhary *et al.* (2017) reported that a management system is considered sustainable if CMI value is greater than 100 (control). Therefore, *Leucaena leucocephala,* Maize Stover, *Chromolaena odorata* and Neem clippings better in enhancing sustainably the quality of this soil.

3.4. Soil aggregate distribution and stability

Plant residues incorporation significantly ($p \leq 0.05$) influenced soil aggregation and stability (Table 5). Specifically, *Chromolena odorata* (20 and 10 t ha^{-1}), Maize Stover (20 t ha^{-1} and 10 t ha^{-1}) and *Leucena leucocephala* (20 t ha^{-1}) had corresponding values ranging from 39.65% to 27.70% for 5.66-2.00 mm aggregate fraction as compared with control plot (17.12%). The overall relative distribution within the aggregate sizes showed higher proportion of macro-aggregate (> 0.25 mm) fractions over the micro-aggregate (< 0.25 mm) in soils amended with the plant materials (Table 5). This trend summarized by the aggregate ratio (AR) values (Table 5) showed *Chromolena odorata* (11.97) and Maize Stover (11.30) followed by *Leucena leucocephala* (10.74) applied at 10 t ha^{-1} each binds the smaller aggregates into larger aggregates thus improving the soil aggregation better than other residues.

The overall stability of the soil further assessed by mean weight diameter (MWD) showed significant increase in MWD in soils where the plant residues were applied over the control (Table 5). The highest MWD values 2.02 mm and 1.92 mm were obtained with *Chromolena odorata* 20 and 10 t ha^{-1}) respectively. This was followed by *Panicum maximum* (1.86 mm) at 20 t ha^{-1}; Maize Stover at 20 t ha^{-1} (1.85 mm) and 10 t ha^{-1} (1.76 mm); and *Leucena leucocephala* (1.69 mm) applied at 20 t ha^{-1}. With the structural stability index (SI) of < 5% and > 7% indicating structurally degraded soil due to loss of OC and sufficient OC to maintain stable soil respectively (Pieri, 1992); the effectiveness of the applied plant materials to enhance the OC

Table 3. Organic carbon fractions relative to plant residues incorporated

Treatment	Rate (t ha^{-1})	CPI	LI	CMI
Control	0	1.00^{c}	1.00^{ac}	100^{b}
BC	10	1.25^{bc}	0.80^{ac}	98.5^{b}
	20	1.43^{abc}	0.72^{ac}	98.0^{b}
CO	10	1.51^{ab}	0.67^{bc}	97.7^{b}
	20	1.57^{ab}	0.85^{ab}	132.9^{ab}
LL	10	1.65^{ab}	0.65^{ab}	97.5^{b}
	20	1.85^{a}	0.93^{ab}	166.6b
MS	10	1.24^{bc}	1.29^{a}	137.9^{ab}
	20	1.58^{ab}	0.81^{ab}	132.1^{ab}
NC	10	1.42^{abc}	0.71^{ab}	98.0^{b}
	20	1.40^{abc}	1.01^{ab}	134.8^{ab}
PM	10	1.66^{ab}	0.59^{b}	97.2^{b}
	20	1.45^{abc}	0.72^{ab}	98.0^{b}

CP- Carbon Pool Index; LI- Lability Index; CMI-Carbon Management Index
Values in columns for the same parameters with different letters indicate significant difference at $p \leq 0.05$

levels and consequent improvement in stability of this fragile tropical was shown by SI results presented in Table 5. The SI trend with the residues when compared with control also confirmed the superiority of *Leucena leucocephala* and *Panicum maximum* to significantly improve the quality of this soil.

Soil stability at micro-aggregate scale shows higher value of DR and CDR to mean greater ability of soil to disperse; while higher values of CFI and ASC indicate better soil aggregation. Results from this study (Table 5) showed DR when compared with control (0.59) was marginally reduced with the addition of Neem Clippings 20 t ha^{-1} (0.56), followed by *Chromolaena odorata* applied at 10 t ha^{-1} and 20 t ha^{-1} (0.57) and Banana Clippings 10 t ha^{-1} (0.57). The results further showed that Clay dispersion ratio (CDR) was reduced with the application of Neem Clippings applied at 10 t ha^{-1} (0.57), *Chromolaena odorata* at 10 t ha^{-1} (0.58) compared with control which was (0.62). Results also showed increase in Clay flocculation index (CFI) with application of residues except plots amended with Maize Stover at 10 t/ha where there was significant ($p \leq 0.05$) 38% reduction over the control. Specifically, CFI was highest in soil treated with Neem clippings 10 t ha^{-1} (0.43) which was 13% higher than control, followed by *Chromolaena odorata* applied at 10 t ha^{-1} (0.42) and *Leucaena leucocephala* at 20 t ha^{-1} (0.42). Aggregated silt and clay (ASC) was highest in the plots treated with *Chromolaena odorata* 10 t ha^{-1} (7.53) and 20 t ha^{-1} (6.87), and Neem Clippings applied at 20 t ha^{-1} (6.87). This agrees with observation of Igwe and Nwakocha (2006) who reported that higher values of CFI and ASC indicate that a soil is better stable and not prone to degradation. Overall observation in this study agrees with that of Hati *et al.* (2008) that incorporation of organic residue improved soil structure and aggregate stability. Also, Parwada and Tol (2018) in an incubation study of soil under varying litter quality observed improvement in water-stable aggregates, mean-weight diameter and whole soil stability index; but concluded that not all litters are suitable to enhance soil aggregation.

Table 5. Aggregate size distribution and aggregate stability indices

Treatment	Rate (t ha^{-1})	Aggregate Size (mm) 5.66-2.0	2.0-1.0	1.0-0.50	0. 50-0.25	<0.25	AR	MWD (mm)	Aggregate Stability Indices SI (%)	DR	CDR	CFI	ASC
Control	0	17.12	18.15	19.07	17.54	28.12	2.60f	1.17^{f}	11.23^{c}	0.59^{b}	0.62^{b}	0.38^{a}	6.53^{ab}
BC	10	20.98	23.57	24.77	16.71	13.97	8.16^{bcd}	1.42^{cf}	15.37^{bc}	0.59^{b}	0.64^{ab}	0.36^{ab}	6.20^{abc}
	20	22.00	23.15	24.22	19.35	13.94	7.29^{dc}	1.46^{c}	17.24^{abc}	0.65^{ab}	0.64^{ab}	0.36^{ab}	5.20^{bc}
CO	10	36.03	22.17	20.23	13.65	7.91	11.97^{a}	1.93^{ab}	15.42^{bc}	0.57^{b}	0.58^{b}	0.42^{a}	7.53^{a}
	20	39.65	19.64	20.80	11.17	8.74	4.63^{cf}	2.02^{a}	17.74^{ab}	0.57^{b}	0.63^{ab}	0.37^{ab}	6.87^{ab}
LL	10	17.12	18.15	19.07	17.54	28.12	10.74^{abc}	1.49^{dc}	19.55^{ab}	0.63^{ab}	0.64^{ab}	0.37^{ab}	5.53^{abc}
	20	29.70	20.71	21.51	16.37	11.17	6.79^{dc}	1.69^{bc}	22.97^{a}	0.58^{b}	0.59^{b}	0.42^{a}	6.20^{abc}
MS	10	31.15	22.89	22.54	11.95	11.47	11.3^{ab}	1.76^{ad}	14.41^{bc}	0.58^{b}	0.82^{a}	0.18^{b}	6.20^{abc}
	20	33.73	23.13	18.30	16.32	8.53	7.62^{cde}	1.85^{abc}	17.35^{ab}	0.67^{ab}	0.69^{ab}	0.31^{ab}	5.53^{abc}
NC	10	26.45	21.63	22.36	17.29	12.27	6.29^{dc}	1.59^{cde}	16.90^{abc}	0.63^{ab}	0.57^{b}	0.43^{a}	5.53^{abc}
	20	25.41	21.81	24.35	15.11	13.33	8.04^{cd}	1.56^{de}	15.98^{bc}	0.56^{b}	0.67^{ab}	0.33^{ab}	6.87^{ab}
PM	10	26.21	22.33	22.10	17.63	11.74	6.53^{dc}	1.59^{cde}	20.02^{ab}	0.72^{a}	0.60^{b}	0.40^{a}	4.20^{c}
	20	26.33	22.28	23.05	16.60	12.73	6.88^{dc}	1.86^{abc}	17.74^{ab}	0.66^{ab}	0.59^{b}	0.41^{a}	4.87^{bc}

LSD(0.05) Aggregate sizes = 1.07; Treatment x Aggregate sizes = 3.87

AR, Aggregate ratio; MWD, Mean-weight diameter; SI, Structural index; DR, Dispersion ratio; CDR, Clay dispersion ratio; CFI, Clay flocculation index; ASC, Aggregated silt + clay.
Values in columns for the same parameters with different letters indicate significant difference at $p \leq 0.05$

3.5. Relationships of soil aggregate properties and carbon parameters

Correlation between the organic carbon parameters and aggregate stability indices presented in Table 7 to Table 11 was used to assess the role of individual OC fractions and their derivative in stability of this soil. Results showed significant ($p < 0.01$) positive correlations between structural index (SI) and total OC (C_T), stable OC (C_{NL}) and carbon pool index (CPI) irrespective of the plant residues. Negative correlations were also obtained between aggregate ratio and the OC parameters with addition of the residues. High significant negative corrections between AR and CT ($r = -0.919$, $p < 0.001$), C_{NL} ($r = -0.942$, $p < 0.001$), CPI ($r = -0.950$, $p < 0.001$), and positive correlation with LI ($r = 0.770$, $p < 0.05$) were obtained with addition of Maize Stover only (Table 9). The relationship between the MWD and OC parameters as shown with addition of *Leucaena leucocephala* (Table 8) being of higher quality (CN = 4.85, Table 2) compared with other plant materials show high positive correlations between MWD and the labile OC fraction ($r = 0.634$), lability index ($r = 0.686$) and CMI ($r = 0.641$). The relationship between the micro-aggregate indices and the OC parameters were very weak because the fine soil textural components are the main determinant of micro-aggregate stability. However, there were negative relationship between dispersion ratio and C_L ($r = -0.803$, $P < 0.05$), CMI ($r = -0.797$, $P < 0.05$), and LI (-0.701, $P > 0.05$) in soils treated with Neem clippings (Table 10). While positive correlation indicates contribution to stabilization of the soil aggregates, negative correlation implies possibility of soil disaggregation with elevated content of the individual organic carbon fraction.

Table 6. Linear correlation between carbon fractions and aggregate stability indices for soils treated with Banana clippings residue

	C_T	C_L	C_{NL}	CPI	LI	CMI	AR	MWD	SI	DR	CDR	CFI	ASC
CT	1												
CL	0.615*	1											
CNL	0.987*	0.615*	1										
CPI	0.987**	0.597*	0.978**	1									
LI	-0.945**	-0.521*	0.945**	-0.984**	1								
CMI	-0.927**	-0.493	-0.927**	-0.974**	0.989**	1							
AR	-0.318	-0.811**	-0.318	-0.305	0.220	0.199	1						
MWD	-0.697*	0.145	0.697*	0.624*	-0.541*	-0.517*	0.098	1					
SI	0.944**	0.760*	0.944**	0.960**	0.933**	-0.921**	-0.542*	0.452	1				
DR	-0.064	0.035	-0.064	-0.208	0.370	0.409	-0.267	0.329	-0175	1			
CDR	-0.674*	-0.721*	-0.674*	-0.760*	0.804**	0.811**	0.477	-0.087	-0.833**	0.595	1		
CFI	0.674*	0.721*	0.674*	0.760*	-0.804**	-0.811**	-0.477	0.087	0.833**	-0.595	0.411	1	
ASC	0.092	-0.174	0.092	0.219	-0.379	-0.416	0.486	-0.173	0.115	0.963**	-0.471	0.471	1

CP- Carbon Pool Index; LI- Lability Index; CMI-Carbon Management Index
Values in columns for the same parameters with different letters indicate significant difference at $p \leq 0.05$

Table 7: Linear correlation between carbon fractions and aggregate stability indices for soils treated with C. odorata residue

	C_T	C_L	C_{NL}	CPI	LI	CMI	AR	MWD	SI	DR	CDR	CFI	ASC
C_T	1												
C_L	0.175	1											
C_{NL}	0.991**	0.044	1										
CPI	0.971**	0.047	0.979**	1									
LI	-0.163	0.941**	-0.291	-0.292	1								
CMI	0.160	0.996**	0.029	0.032	0.946**	1							
AR	-0.478	-0.358	-0.437	-0.498	-0.162	-0.350	1						
MWD	0.407	0.528*	0.343	0.383	0.358	0.521*	-0.739*	1					
SI	0.683*	0.359	0.645*	0.620*	0.113	0.349	-0.766*	0.885**	1				
DR	0.532*	-0.149	0.560*	0.515*	-0.336	-0.158	-0.241	0.607*	0.742*	1			
CDR	0.140	0.446	0.082	0.188	0.355	0.442	-0.455	0.864**	0.563*	0.470	1		
CFI	-0.140	-0.446	-0.082	-0.188	-0.355	-0.442	0.455	-0.864**	-0563*	-0.470	-1	1	
ASC	-0.257	0.040	-0.261	-0.225	0.101	0.004	0.331	-0.748*	-0.759*	-0.914**	-0.623*	0.623*	1

All abbreviations are as described in Table 6. *Significant at $P \leq 0.05$ ** Significant at $P \leq 0.01$

Table 8: Linear correlation between carbon fractions and aggregate stability indices for soils treated with L. leucocephala residue

	C_T	C_L	C_{NL}	CPI	LI	CMI	AR	MWD	SI	DR	CDR	CFI	ASC
C_T	1												
C_L	0.035	1											
C_{NL}	0.996**	-0.051	1										
CPI	0.991**	0.017	0.989**	1									
LI	-0.543*	0.811**	-0.613*	-0.560*	1								
CMI	0.004	0.999**	-0.083	-0.013	0.829**	1							
AR	-0.526*	-0.643*	-0.470	-0.474	-0.226	0.624*	1						
MWD	-0.187	0.634*	-0.242	-0.263	0.686*	0.641*	-0.626*	1					
SI	0.924**	0.125	0.912**	0.875**	-0.437	0.092	-0.682*	-0.009	1				
DR	-0.539*	0.095	-0.546*	-0.479	0.294	0.106	0.369	-0.361	-0.472	1			
CDR	-0.272	-0.168	-0.257	-0.231	-0.100	-0.169	0.183	-0.446	-0.132	-0.844**	1		
CFI	0.272	0.168	0.257	0.231	0.100	0.169	-0.183	-0.446	-0.132	-0.844**	-0.118	1	
ASC	0.478	-0.106	0.487	0.475	-0.268	-0.111	-0.139	0.161	-0.246	-0.888**	-0.889**	0.889**	1

All abbreviations are as described in Table 6. *Significant at P ≤ 0.05 ** Significant at P ≤ 0.01

Table 9. Linear correlation between carbon fractions and aggregate stability indices for soils treated with Maize Stover residue

	C_T	C_L	C_{NL}	CPI	LI	CMI	AR	MWD	SI	DR	CDR	CFI	ASC
C_T	1												
C_L	0.028	1											
C_{NL}	0.995**	-0,069	1										
CPI	0.990**	-0.089	0.997**	1									
LI	-0.568*	0.784*	-0.643*	-0.647*	1								
CMI	-0.054	0.996**	-0.151	-0.168	0.837*	1							
AR	-0.919**	0.254	-0.942**	-0.950**	0.770*	0.333	1						
MWD	-0.078	0.172	-0.095**	-0.123	0.028	0.148	-0.093	1					
SI	0.959**	-0.015	0.958**	0.945**	-0.551*	-0.089	-0.818**	-0.275	1				
DR	0.122	-0.388	0.159	0.106	-0.478	-0.416	-0.256	0.516*	0.148	1			
CDR	0.477	-0.366	0.512*	0.566*	-0.465	-0.382	-0.475	-0.737*	0.508*	-0.495	1		
CFI	-0.477	0.366	-0.512*	-0.566*	0.465	0.382	0.475	0.737*	-0.508*	0.495	-1	1	
ASC	0.211	0.251	0.186	0.248	0.123	0.234	-0.200	-0.238	0.065	-0.851**	0.597*	-0.597*	1
ASC	0.478	-0.106	0.487	0.475	-0.268	-0.111	-0.139	0.161	-0.246	-0.888**	-0.889**	0.889**	1

All abbreviations are as described in Table 6. *Significant at P ≤ 0.05 ** Significant at P ≤ 0.01

Table 10. Linear correlation between carbon fractions and aggregate stability indices for soils treated with Neem Clippings residue

	C_T	C_L	C_{NL}	CPI	LI	CMI	AR	MWD	SI	DR	CDR	CFI	ASC
C_T	1												
C_L	-0.333	1											
C_{NL}	-0.993**	-0.446	1										
CPI	-0.974**	-0.468	-0.985**	1									
LI	-0.541*	-0.972**	-0.640*	-0.663*	1								
CMI	-0.347	-0.992**	-0.459	-0.481	0.975**	1							
AR	-0.243	-0.060	-0.223	-0.225	-0.009	-0,057	1						
MWD	-0.323	-0.402	0.359	-0.324	-0.416	-0.403	-0.499	1					
SI	-0.738*	-0.183	-0.725*	-0.604*	-0.317	-0.191	0.019	0.409	1				
DR	0.044	-0.803**	-0.145	0.098	-0.701*	-0.797*	-0.045	0.264	-0.143	1			
CDR	0.034	-0.012	0.034	0.076	-0.047	-0.015	0.812**	-0.197	0.108	-0.394	1		
CFI	-0.034	0.012	-0.034	-0.076	0.047	0.015	-0.812**	0.197	-0.108	0.394	-1	1	
ASC	0.088	0.387	0.033	0.167	0.285	0.380	0.38-	-0.179	-0.467	-0.708*	0.071	-0.071	1

All abbreviations are as described in Table 6. *Significant at P ≤ 0.05 ** Significant at P ≤ 0.01

Table 11. Linear correlation between carbon fractions and aggregate stability indices for soils treated with Panicum maximum residue

	C_T	C_L	C_{NL}	CPI	LI	CMI	AR	MWD	SI	DR	CDR	CFI	ASC
C_T	1												
C_L	-0.148	1											
C_{NL}	0.995**	0.148	1										
CPI	0.990**	0.152	0.990**	1									
LI	-0.987**	-0.052	-0.987**	-0.985**	1								
CMI	-0.976**	0.003	-0.976**	-0.982**	-0.997**	1							
AR	-0.337	-0.335	-0.337	-0.432	0.410	0.426	1						
MWD	-0.893**	-0.062	-0.893**	-0.884**	0.947**	0.944**	0.456	1					
SI	0.881**	0.088	0.881**	0.888**	-0.933**	-0.927**	-0.587*	-0.981**	1				
DR	0.319	-0.054	0.319	0.336	-0.407	-0.411	-0.643*	-0.504*	0.507*	1			
CDR	0.730*	-0.281	0.730*	0.663*	-0.793*	-0.727*	0.190	-0.773*	0.675*	-0.013	1		
CFI	-0.730*	0.281	-0.730*	-0.663*	0.793*	0.727*	-0.190	0.773*	-0.675*	0.013	-1	1	
ASC	-0.121	0.114	-0.121	-0.147	0.246	0.254	-0.688*	0.451	-0.477	-0.911**	0-053	-0.053	1
ASC	0.088	0.387	0.033	0.167	0.285	0.380	0.38-	-0.179	-0.467	-0.708*	0.071	-0.071	1

All abbreviations are as described in Table 6. *Significant at P ≤ 0.05 ** Significant at P ≤ 0.01

4. Conclusions

We observed from this study that forms of organic carbon (OC) accumulation in the soil depended on the quality of residues added to the soil as indicated by the CN ratios of the different plant materials over the control. Application of *Leucaena leucocephala* at 20 t ha^{-1} significantly had highest concentrations of the OC fractions, i.e. the total, labile and stable (non-labile) forms of OC; this was followed by *Panicum maximum* applied at 10 t ha^{-1}. Lability and carbon pool index which reflected organic carbon decomposition and accumulation respectively, and soil quality by carbon management index was in the order of *Leucaena leucocephala* > *Panicum maximum* > *Chromolaena odorata*. This study also showed that *Chromolaena odorata* followed by *Leuceana leucocephala* at 20 t ha^{-1} and *Panicum maximum* at 10 tons/ha improved the soil aggregation and stability better. Overall improvement of the soil quality as influenced by the observed C dynamics was higher with addition of *Leucaena leucocephala, Panicum maximum* and *Chromolaena odorata* over other materials applied. These plant materials are weeds which grow luxuriantly in most humid tropical environment, and are therefore suitable to provide necessary short-term remedy against erosion risk.

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