Soil organic matter fractions under different agricultural land-use in Ile-Ife, Nigeria

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The study investigated the impact of long-term agricultural land-use on the distribution of density and particulate fractions of soil organic matter and examined the potential of soil aggregate size fractions to stabilize soil organic matter. Soil samples were collected at 0-15 and 15-30 cm soil depths from paddock, undisturbed secondary forest, continuously cropped land, teak, oil palm, and cacao plantations at the Teaching and Research Farm, Obafemi Awolowo University, Nigeria. The soil samples were air-dried, and segregated into three different aggregate-size classes (0.063-0.25, 0.25-1 and 1-2 mm). Bulk soil and soil aggregates were analyzed for particulate, and density organic matter fractions. Soil organic matter and total nitrogen contents of the density fractions were determined. The soil's content of particulate organic matter fraction was significantly highest under oil palm plantation (30.96 gkg^{-1}) and least under continuous cultivation (9.8 gkg^{-1}). Cacao, teak, and secondary forest land-use types had higher heavy organic matter fractions (HFOM) of 18.92, 13.93 and 10.49 gkg^{-1} respectively, while soil light organic matter fraction (LFOM) contents were not significantly different under the land-use types except continuously cropped land that had the least content. Therefore, using HFOM as index, cultivation of tree crops and afforestation stores and protect carbon in the soil. This implies that, rather than leaving the land to native fallow, cultivation of the studied economic tree crops will positively impact the carbon sequestration potential of the land. The HFOM, LFOM, and C:N ratio was higher in 0.063-0.25 mm aggregate-size class. Hence, smaller sized soil aggregates (0.063-0.25 mm) were better at storing and stabilizing soil organic matter compared to the larger size aggregates.

Keywords: Soil organic matter, agricultural land-use, light fraction organic matter, heavy fraction organic matter, particulate organic matter

Soil organic matter (SOM) is an indicator of soil fertility, and strongly affects soil physical, chemical and biological properties. It can be partitioned into different fractions based on its physical and chemical characteristics. Physical fractionation has been adopted for the quantification of SOM stability (Lavallee et al. 2020; Nakatsuka et al. 2020). The critical characteristics of SOM that determines its reactivity, composition, and fate are particle size and density (Wakeham and Canuel 2016). Particulate SOM fraction is SOM with a size greater than 0.05 mm (Duxbury et al. 1989). It consists of partially decomposed plant and animal residue and are organic fragments with recognizable cellular structure (Lavallee et al. 2020). Particulate fraction has been used as an index for the SOM storage capacity of different land-use management systems (Sá and Lal 2009). Densimetrically, SOM is fractionated into light fraction having density <1.6 gcm^{-3} and heavy fraction with density >1.6 gcm^{-3} (Sollins et al. 2006). Density fraction explicates the association of SOM with soil mineral matter, SOM stability and turnover times (Wakeham and Canuel 2016; Prietzel et al. 2020). The light fraction contains predominantly easily decomposable plant and animal residue, they are commonly referred to as plant-like, and less stable fraction with high carbon concentration (Golchin et al. 1994). The heavy fraction represents the mineral-associated portion which is less accessible to decomposers and their enzymes; they are more stable and thus, protected parts of SOM (Totsche et al. 2018). It is a major sink for carbon storage in soil and it has little mineralizable carbon (Whalen et al. 2000). Hence, heavy SOM fraction can be used as an indication for carbon sequestration and carbon protection in soil.

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The dynamics of SOM is significantly affected by land-use, which can either lead to sequestration or emission of carbon (Alcantara et al. 2016), and the emission is mainly in the form of CO_2 (a major contributor to global warming). While most agricultural activities have been identified as major sources of CO_2 emission (such as deforestation, bush burning, rearing of ruminant animals, etc.) (DeFries et al. 1999; Marland et al. 2000), it is also possible for some agricultural activities to reverse these negative effects and promote soil carbon sequestration in addition to other benefits of food security and sustainability of the systems (Lal 2016). Sequestering carbon in soil offers a valuable offset for greenhouse gas emissions (Schaefer et al. 2020). Most studies focused on quantifying carbon stock in soil (Alcantara et al. 2016; Fang et al. 2018), while very few quantifies how much of these stocks are protected from mineralization (Olson et al. 2014). Carbon stored in the soil are not entirely protected from decomposition (Olson et al. 2014), and are thus, potential contributors to global warming. Fractionation of SOM is crucial to understanding its dynamics, decomposition and stabilization processes (Poeplau et al. 2018; Lavallee et al. 2020). It has also been established that fractionation of SOM is more effective than total SOM in the evaluation of SOM dynamics due to agricultural use (Guimaraes et al. 2013).

Tropical soils are highly degraded, which has led to drastic reduction in their SOM content (Lal 2004). Thus, they contain lower carbon pool than their potential capacity (Poeplau and Don 2013). Being a tropical rainforest agro-ecological zone, the dominant agricultural land-use types in Southwestern Nigeria are tree crop plantations and arable farms. Nigeria's economy is currently being diversified from oil-based to agricultural-based amongst others. In doing this, more forests (most of which are secondary forests) will be converted to agricultural land. Also, the Federal Government of Nigeria has concluded plans to establish confined grazing areas within the southern part of the country to prevent reoccurrence of conflict between northern herders and southern farmers. These will lead into an increase in the establishment of paddocks within the southern region, including Southwestern Nigeria. Therefore, there is going to be an increase in the establishment of these agricultural land-use types (arable farm, paddock and tree crop plantations) across the region. The need to assess the distribution of SOM fractions within these land-use types prompted this study. Nearly 90% of SOM in surface soils were reported to be located within soil aggregates (Jastrow et al. 1996), while the degree of SOM mineralization was dependent on aggregate size (Gregorich et al. 2003). John et al. (2005) observed that SOM stored in microaggregates (<250 μm) had higher turnover time compared with that of macroaggregates (>250 μm). Hence, the suggestion that small-sized aggregate protects SOM than larger aggregates (Oyedele et al. 2014). Therefore, there is a need to quantitatively evaluate this theory. The aim of this study is to investigate the distribution of SOM fractions under long-term agricultural land-use types, and the distribution of these fractions within soil aggregate of different size classes. This is with the intention to assess the potential of the land-use types to sequester SOM through their impact on various fractions of SOM and the SOM protection potentials of different soil aggregate-size classes. Research questions are: (i) how do land-use types affect the distribution of SOM fractions; and (ii) is SOM protection potentials of soil aggregates in the humid tropic region dependent on aggregate size?

Materials and methods

Sampling site

Soil samples were collected from the Teaching and Research Farm, Obafemi Awolowo University, Ile-Ife, Nigeria. It lies approximately between Latitudes 7^{o} 54' 277''

N and 7° 56'074'' N and Longitudes 4° 54' 155'' E and 4° 55'861'' E. It is in the rainforest ecosystem of the Southwestern part of Nigeria with a mean annual rainfall of about 1500 mm. The soils were classified as Ferric Acrisol (IUSS World Reference Base 2015). Soil samples were collected from six land-use types as follow: paddock (PL), teak (*Tectona grandis*) plantation (TL), oil palm (*Elaeis guineensis*) plantation (OL), cacao (*Theobroma cacao*) plantation (CL), secondary forest (SFL) and continuously cropped land (CCL). The paddock was established about 20 years prior to this study and it had been under sheep and goat grazing since then. The teak, oil palm and cacao plantations have been established 35 years before this study. The secondary forest has been left undisturbed for over 35 years while the continuously cropped land had been tilled continuously every year for about 20 years, and it had been continuously cropped with maize (*Zea mays*). Akinde et al. (2020) gave detailed descriptions of the study area and land-use types.

Soil sampling and analyses

The soil was sampled at two depths; 0-15 and 15-30 cm from each land-use type. Each land-use type was divided into three units based on physiography (upper, middle and lower slopes) with each unit serving as a block/replicate. Selected physical and chemical properties of soil under each land-use type were determined. Ten soil samples were randomly collected from each unit using a sampling tube. Soil samples collected were bulked, air dried, gently crushed with hands and sieved through 2 mm sieve. Sieved soils were segregated into three different aggregate classes (0.063-0.25, 0.25-1 and 1-2 mm) using Endecott test sieve shaker (SER No. 6437) at 240 rpm for 5 minutes. The SOM in whole soil and aggregate-size class were fractionated into particulate and density organic matter fractions.

Determination of selected physical and chemical properties

Modified hydrometer method was used in determining the soil separates with 0.2 M NaOH solution as dispersing agent as described by Gee and Or (2002). Textural triangle was used to ascertain the textural class of the soil samples. Soil Bulk density was determined using the cylindrical core method. Soil pH by digital pH meter (Walk lab Ti 9000) in a 2:1 suspension of 0.01 M $CaCl_2$ solution to soil ratio; cations exchange capacity using 1 N NH_4OAc solution at pH 7 (Sumner and Miller 1996); and available phosphorus using Bray-1 method (Kuo 1996).

Particulate organic matter fractionation

The SOM was fractionated into particulate organic matter fraction (POM) according to the method used by Figueiredo et al. (2010). Exactly 20 g of soil sample was weighed into shake-bottle, 70 ml of 0.2 M NaOH solution was added. The soil-NaOH mixture was shaken at 350 oscillations per minute for 10 minutes on a horizontal shaker. The mixture was then washed and sieved through a 53 µm sized sieve, the residue representing particulate organic carbon (POM) was then oven-dried at 60°C for 24 hours. The carbon content of the residue (POM) was determined using the chromic acid digestion method (Nelson and Sommers 1996).

Density organic matter fractionation

Density organic matter fractionation of the SOM was carried out according to the method described by Gregorich and Ellert (1993) with modification in the density solution (using $ZnCl_2$ solution of density 1.7 gcm^{-3}). Exactly 10 g of soil sample was weighed in a centrifuge tube and 40 ml of $ZnCl_2$ (of density 1.7 gcm^{-3}) was added. The mixture was shaken at 350 oscillations per minute for 6 minutes on a horizontal shaker, then centrifuged at 1000 g for five minutes. The supernatant was decanted and filtered through 53 µm sieve. The residue represents light organic matter fraction (LFOM). An additional 40 ml of $ZnCl_2$ was added to the precipitate, it was shaken and centrifuged accordingly. The supernatant was decanted and filtered through 53 µm sieve, the residue was added to the former LFOM. The LFOM was washed with 0.01 M $CaCl_2$ solution and distilled water respectively, then oven-dried at 65°C for 24 hours. The precipitate (representing the heavy fraction organic matter {HFOM}) was shaken with 40 ml 0.01 M $CaCl_2$ solution at 350 oscillations per minute for 6 minutes on a horizontal shaker, then centrifuged at 1000 g for 5 minutes, the supernatant was discarded. The resulting precipitate was then shaken with 40 ml distilled water at 350 oscillations per minute for 6 minutes on a horizontal shaker, then centrifuged at 1000 g for 5 minutes, and the supernatant was also discarded. The precipitate was then oven-dried at 65°C for 24 hours. The density organic matter fractions (LFOM and HFOM) were analyzed for their carbon and nitrogen contents using chromic acid digestion method (Nelson and Sommers 1996) and micro-Kjeldahl digestion procedure (Bremner 1996) respectively.

Statistical analysis

The experiment was arranged as a randomized complete block design while statistics were done using SAS software (9.0). Data obtained were subjected to analysis of variance (ANOVA) using general linear model procedure and means were separated using Duncan's Multiple Range Test at $p \leq 0.05$.

Results

Selected physical and chemical properties

The soils in the study area irrespective of land-use were predominantly sandy loam to sandy clay loam in texture (Table 1). The soil bulk density on the land-use types ranged from 0.94 to 1.55 gcm^{-3} in the surface soil (0-15 cm depth) and 1.40 to 1.63 gcm^{-3} in the subsoil (15-30 cm depth) (Table 2). The pH of the surface soil ranged from 4.71 to 6.01 while that of subsoil ranged from 4.64 to 5.76. The pH across the land-use types falls between ranges of very slightly acidic to strongly acidic. The cation exchange capacity of the land-use types ranged between 2.32 to 3.18 $cmolkg^{-1}$ in the surface soil and 2.69 to 3.09 $cmolkg^{-1}$ in the subsoil. The available phosphorus in the land-use types ranged from 4.13 to 7.60 $mgkg^{-1}$ within the surface soil and from 4.74 to 6.98 $mgkg^{-1}$ within the subsoil.

Analysis of variance of soil organic matter fractions using GLM procedure

It was revealed from the analysis that the variations in POM and HFOM across the land-use types, soil depths, soil aggregate-size classes and their interactions were significant (Table 3). The variations in LFOM and nitrogen content of HFOM were significant across the land-use types, soil depths, soil aggregate-size classes, and the two-way interactions (except for the interaction between land-use and soil aggregate-size class). The nitrogen content of LFOM significantly varied only across the land-use types, soil aggregate-size classes and the interaction between land-use and soil depth. The carbon to nitrogen ratio of HFOM did not significantly vary across the soil aggregate-size classes and the interaction between land-use and soil aggregate-size class. The variation in the carbon to nitrogen ratio of LFOM was not significant across all the factors.

Table 1: Soil particle size distribution for each land-use type at the two soil depths

Land-use	0 – 15 cm Sand	Silt	Clay	Textural class	15 – 30 cm Sand	Silt	Clay	Textural class
	g kg^{-1}				g kg^{-1}			
PL	680	60	260	Sandy clay loam	720	80	200	Sandy loam
OL	730	90	180	Sandy loam	780	70	150	Sandy loam
TL	700	110	190	Sandy loam	720	70	210	Sandy clay loam
SFL	740	100	160	Sandy loam	770	90	140	Sandy loam
CL	660	100	240	Sandy clay loam	560	100	340	Sandy clay loam
CCL	720	100	180	Sandy loam	740	60	200	Sandy loam

PL= Paddock land-use, OL= Oil palm land-use, TL= Teak land-use, SFL= Secondary forest land-use, CL= Cacao land-use, CCL= Continuously cropped land-use.

Table 2: Selected soil physical and chemical properties of each land-use type at the two soil depths

	0-15 cm				15-30 cm			
Land-use	Db (gcm^{-3})	pH ($CaCl_2$)	CEC (cmolkg^{-1})	Avail. P (mgkg^{-1})	Db (gcm^{-3})	pH ($CaCl_2$)	CEC (cmolkg^{-1})	Avail. P (mgkg^{-1})
PL	1.14	5.28	3.18	4.78	1.48	5.05	2.87	4.73
OL	1.34	4.72	2.32	4.13	1.45	4.64	3.05	4.77
TL	1.12	5.51	2.63	5.61	1.45	5.16	2.69	5.40
FL	1.04	5.85	2.44	6.49	1.40	5.76	2.69	5.86
CL	0.94	6.01	3.05	7.60	1.51	5.24	3.15	6.97
CCL	1.55	4.71	2.69	7.39	1.63	4.87	3.09	5.06

PL= Paddock land-use, OL= Oil palm land-use, TL= Teak land-use, SFL= Secondary forest land-use, CL= Cacao land-use, CCL= Continuously cropped land-use, Db= bulk density, CEC= Cation exchange capacity, Avail P= Available phosphorus.

Table 3: Mean square derived from analysis of variance of soil organic matter fractions using general linear model procedure

	Df	POM	HFOM	LFOM	TN(HFOM)	TN (LFOM)	C:N (HFOM)	C:N (LFOM)
		g kg^{-1}						
Rep/Block	2	0.17*	0.09	0.11	0.01	0.04	0.60	1490.24
Land-use	5	1.85**	0.81**	1.13**	0.49**	4.16**	13.04**	1846.58
Soil depth	1	4.42**	0.51*	15.79**	8.74**	0.002	5.47*	230.91
Agg class	2	2.52**	0.63**	4.19**	1.21**	0.58*	1.39	1197.76
Land-use*Soil depth	5	0.50**	0.35**	0.75*	1.18**	0.47**	4.21**	657.32
Soil depth*Agg class	2	0.48**	2.20**	3.26**	0.42*	0.08	33.46**	1563.14
Land-use*Agg class	10	0.93**	0.21*	0.47	0.10	0.16	2.30	1107.17
Land-use*Soil depth*Agg class	10	0.14**	0.35**	0.34	0.04	0.13	4.53**	657.32
Residual	70	0.04	0.08	0.27	0.09	0.13	1.23	1071.23

*, ** indicates mean square significant at 5% and 1% level of probability respectively

Agg class = Soil aggregate-size class, Df = Degree of freedom, POM= Particulate organic matter, HFOM= Heavy organic matter fraction, LFOM= Light organic matter fraction, TN (HFOM) = Total nitrogen of Heavy organic matter fraction, TN (LFOM) = Total nitrogen of Light organic matter fraction, C:N (HFOM)= Carbon to nitrogen ratio of Heavy organic matter fraction, C:N(LFOM)= Carbon to nitrogen ratio of Light organic matter fraction

Particulate organic matter fraction

In the soil surface, the soil under OL had the significantly highest content of POM (30.96 gkg^{-1}) followed by CL (19.95 gkg^{-1}) and SFL (19.78 gkg^{-1}) which were not different from each other (Figure 1). Teak and PL had 15.31 gkg^{-1} and 13.76 gkg^{-1} respectively which were not statistically different from each other, while CCL had significantly least value (9.8 gkg^{-1}).

Cacao land-use (18.75 gkg^{-1}) had the significantly highest content of POM in the subsoil and CCL had the least content (5.85 gkg^{-1}) though not significantly different from that of SFL (8.08 gkg^{-1}) and PL (7.91 gkg^{-1}) (Figure 1). The 1-2 mm aggregate-size class significantly had more POM content in the surface soil (25.45 gkg^{-1}) and subsoil (14.10 gkg^{-1}) (Figure 2). The 0.25-1 and 0.063-0.25 mm aggregate-size classes had similar POM content in the surface soil (14.96 and 14.10 gkg^{-1}, respectively) but significantly different in the subsoil (11.18 and 8.26 gkg^{-1} respectively).

Density fractions of soil organic matter

In the soil surface, soils under CL had the highest contents of HFOM (18.92 gkg^{-1}) which was not significantly different from that of TL (13.93 gkg^{-1}) but significantly higher than other land-use types (Figure 3). The HFOM content of the soil under TL was however not significantly different from under SFL (10.49 gkg^{-1}). For soils under SFL, PL (7.05 gkg^{-1}), OL (5.50 gkg^{-1}) and CCL (3.95 gkg^{-1}) the HFOM were not significantly different from one another, but CCL had numerically least content. However, the LFOM contents within the surface soil were not significantly different across the land-use types except for CCL which had the least. In the subsoil, HFOM content of the land-use types was similar except under SFL (6.19 gkg^{-1}) and CCL (3.10 gkg^{-1}) which had the least value (Figure 3). Within this soil depth OL (4.82 gkg^{-1}) and PL (4.99 gkg^{-1}) had significantly highest LFOM content, CCL (1.55 gkg^{-1}) had the least but not significantly different from under CL (2.24 gkg^{-1}) (Figure 3). The 0.063-0.25 mm aggregate-size class had the highest content of HFOM and LFOM at both the surface soil (17.37 and 28.21 gkg^{-1} respectively) and subsoil (9.63 and 4.3 gkg^{-1} respectively) (Figure 4).

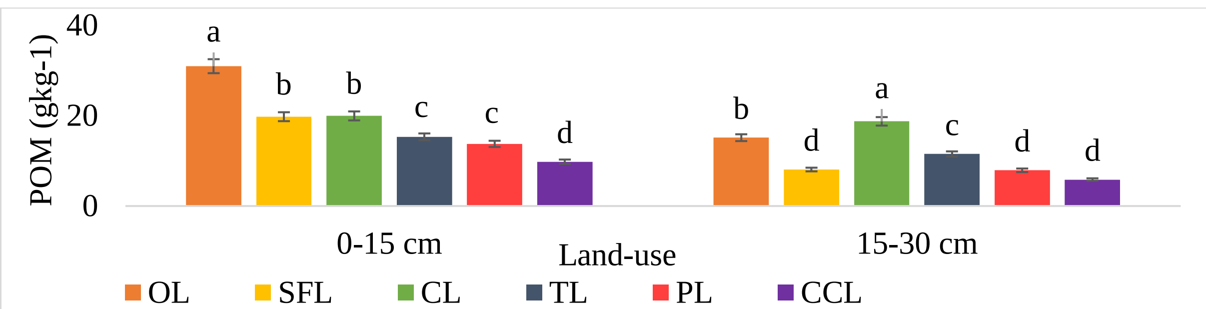

Figure 1: Soil particulate organic matter content of the land-use types at the soil depths

PL= Paddock land-use, OL= Oil palm land-use, TL= Teak land-use, SFL= Secondary forest land-use, CL= Cacao land-use, CCL= Continuously cropped land-use, POM= Particulate organic matter. Means with the same alphabet are not significantly different at 5% probability according to Duncan's Multiple Range Test.

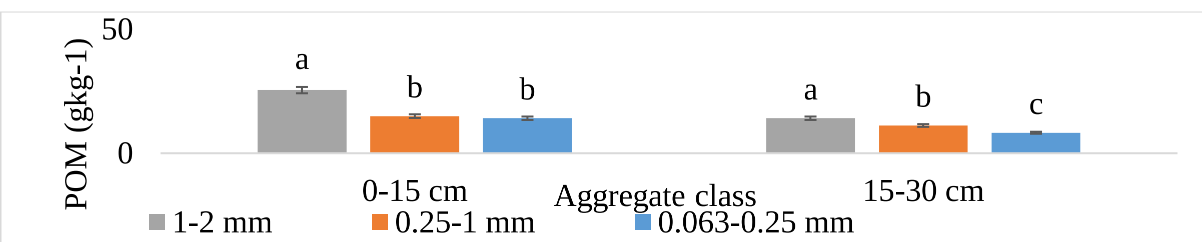

Figure 2: Distribution of particulate organic matter in soil aggregate-size classes at the soil depths

POM= Particulate organic matter. Means with the same alphabet are not significantly different at 5% probability according to Duncan's Multiple Range Test.

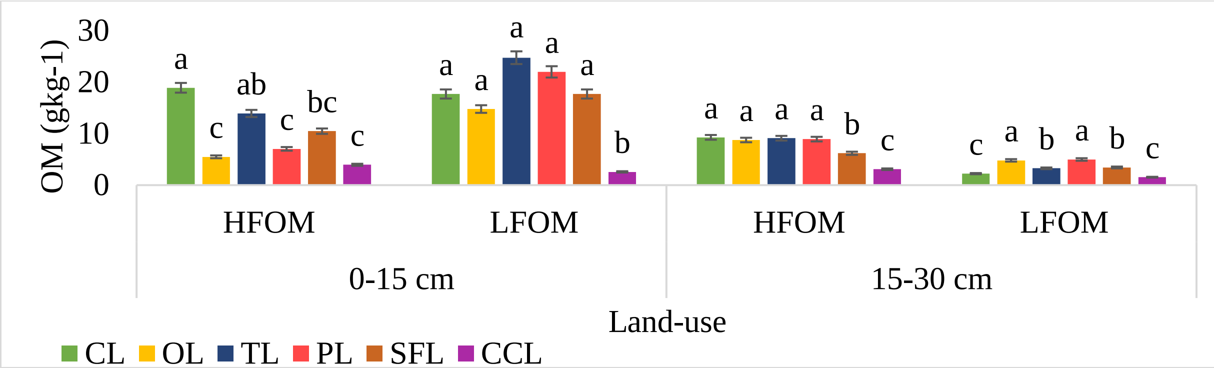

Figure 3: Densimetric soil organic matter fractions of the land-use types at the soil depths

PL= Paddock land-use, OL= Oil palm land-use, TL= Teak land-use, SFL= Secondary forest land-use, CL= Cacao land-use, CCL= Continuously cropped land-use, OM= Organic matter, HFOM= Heavy organic matter fraction, LFOM= Light organic matter fraction. Means with the same alphabet in each fraction are not significantly different at 5% probability according to Duncan's Multiple Range Test.

Total nitrogen of soil organic matter density fractions

Nitrogen (N) contents of HFOM under the land-use types within the surface soil were similar except under OL (1.73 gkg^{-1}) and CCL (1.6 gkg^{-1}) which were statistically similar (Figure 5). Similarly, N content of LFOM fraction under the land-use types within this soil depth was not different from one another except under SFL (1.58 gkg^{-1}) which had significantly highest and CCL (0.18 gkg^{-1}) which had the significantly least value (Figure 5). Likewise in the subsoil, N content of HFOM was similar under the land-use types except under CCL (1.82 gkg^{-1}) which was the highest (Figure 5). However, N content of LFOM in the subsoil was not significantly different under PL (1.36 gkg^{-1}), SFL (1.41 gkg^{-1}) and OL (1.29 gkg^{-1}). Teak land-use had 0.82 gkg^{-1}, whereas, contents under CL (0.37 gkg^{-1}) and CCL (0.11 gkg^{-1}) were statistically similar. The 0.063-0.25 mm aggregate-size class had the highest N content in HFOM and LFOM at both surface soil (2.5 and 0.96 gkg^{-1}, respectively) and subsoil (1.71 and 1.08 gkg^{-1}, respectively) (Figure 6).

Carbon to nitrogen (C:N) ratio of density fractions

The C:N ratio of HFOM in the surface soil under CL (4.05) was significantly highest. Though CCL (1.47) had the least value which was significantly lower than that of TL (2.8), but it was statistically the same as SFL, OL and PL (Figure 7). Within the same soil depth, CL (21.89) had the highest C:N in the LFOM which was statistically not different from that of TL (14.71) and PL (16.73), which in turn were not different from SFL (6.18), OL (9.04) and CCL (7.83). In the subsoil, C:N ratio of HFOM was only significantly different under CCL which was the least. The C:N ratio of LFOM in this soil depth was surprisingly not statistically different from one another under all the land-use types, but CL had the highest numerical value (15.12). The C:N ratio of both HFOM and LFOM in the surface soil was highest in the 0.063-0.25 mm aggregate-size class (3.61 and 20.29 respectively) (Figure 8). Though 0.063-0.25 mm aggregate-size class had the highest C:N ratio (3.72) in HFOM in the subsoil, 0.25-1 mm aggregate-size class had the highest C:N ratio (8.55) in LFOM which was not statistically different from others.

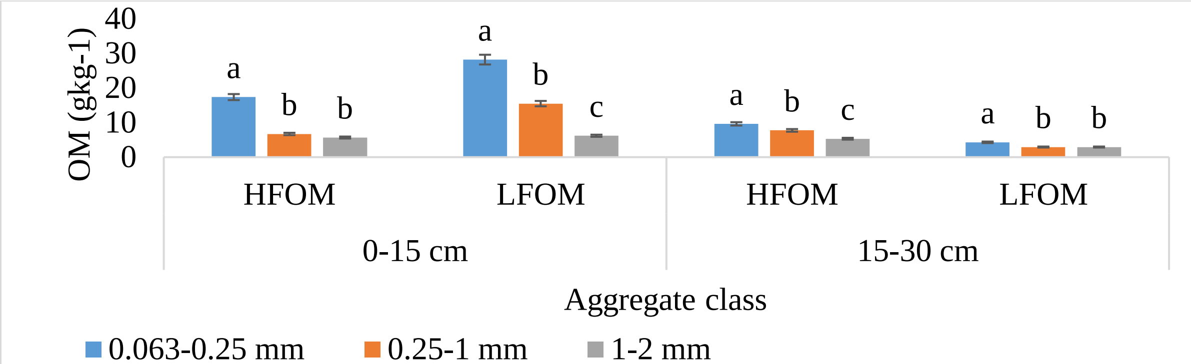

Figure 4: Distribution of densimetric soil organic matter fractions in soil aggregate-size classes at the soil depths

OM= Organic matter, HFOM= Heavy organic matter fraction, LFOM= Light organic matter fraction. Means with the same alphabet in each fraction are not significantly different at 5% probability according to Duncan's Multiple Range Test.

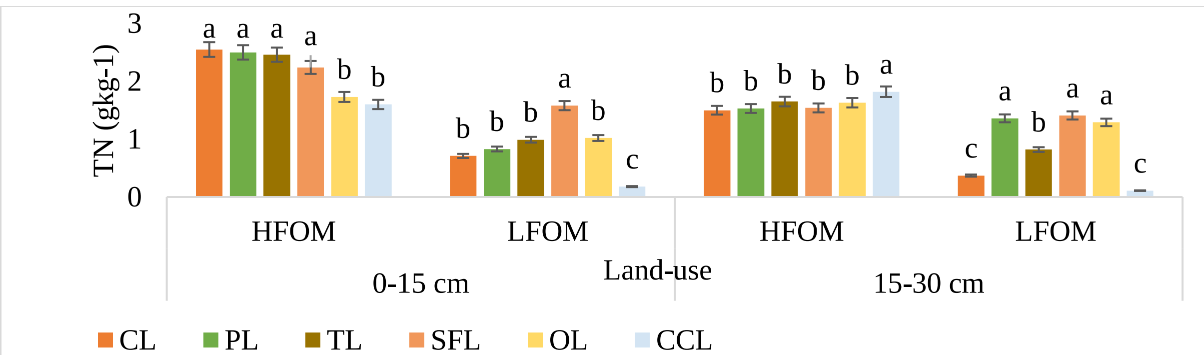

Figure 5: Total nitrogen of the density fractions across the land-use types at the soil depths

PL= Paddock land-use, OL= Oil palm land-use, TL= Teak land-use, SFL= Secondary forest land-use, CL= Cacao land-use, CCL= Continuously cropped land-use, TN= Total nitrogen, HFOM= heavy fraction organic matter, LFOM= light fraction organic matter. Means with the same alphabet in each fraction are not significantly different at 5% probability according to Duncan's Multiple Range Test.

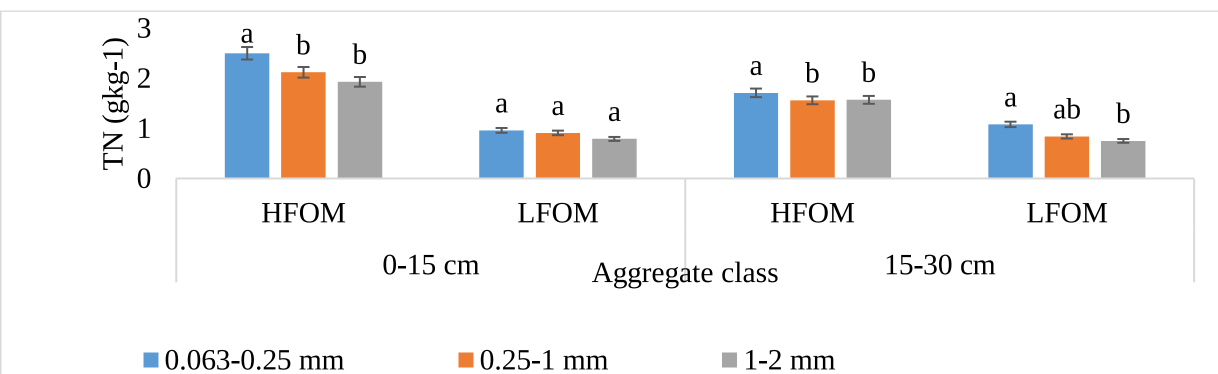

Figure 6: Distribution of total nitrogen of the density fractions across aggregate-size classes at soil depths

TN= total nitrogen, HFOM= heavy fraction organic matter, LFOM= light fraction organic matter. Means with the same alphabet in each fraction are not significantly different at 5% probability according to Duncan's Multiple Range Test.

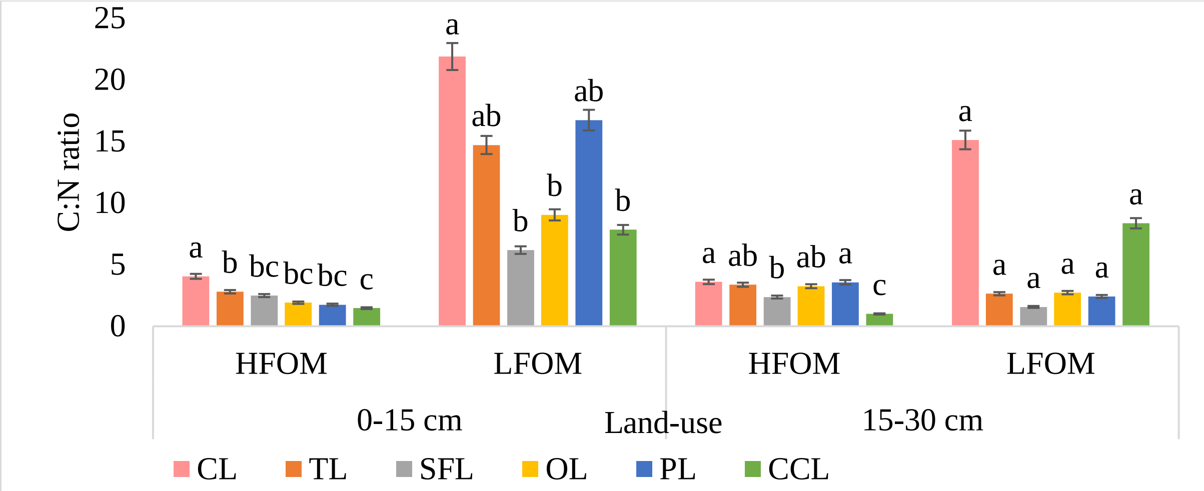

Figure 7: Carbon to nitrogen ratio of the density fractions across the land-use types at the soil depths

PL= Paddock land-use, OL= Oil palm land-use, TL= Teak land-use, SFL= Secondary forest land-use, CL= Cacao land-use, CCL= Continuously cropped land-use, C:N ratio= Carbon to nitrogen ratio, HFOM= heavy fraction organic matter, LFOM= light fraction organic matter. Means with the same alphabet in each fraction are not significantly different at 5% probability according to Duncan's Multiple Range Test.

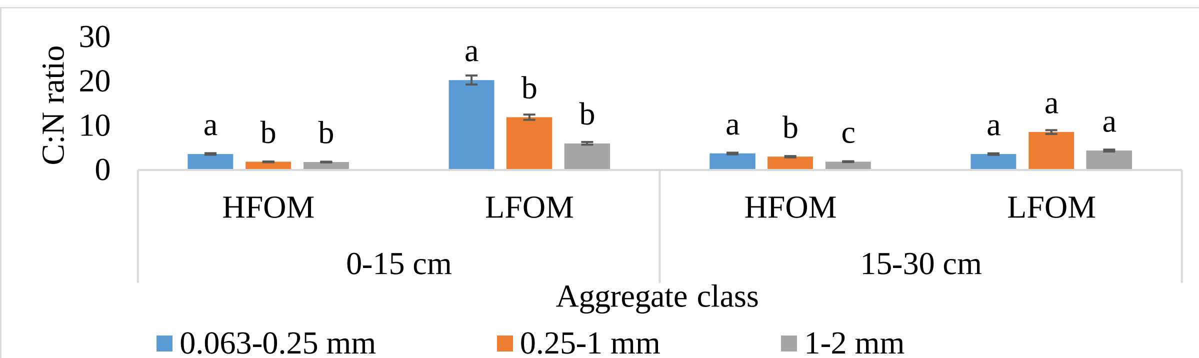

Figure 8: Distribution of carbon to nitrogen ratio of the density fractions across aggregate-size classes at soil depths

C:N ratio = Carbon to nitrogen ration, HFOM= heavy fraction organic matter, LFOM= light fraction organic matter. Means with the same alphabet in each fraction are not significantly different at 5% probability according to Duncan's Multiple Range Test.

Discussion

Particulate organic matter fraction

The concentration of SOM is dependent on both the belowground and underground biomass (plant root inclusive) and inputs from litter fall, root exudation and residue incorporation (Zhang et al. 2013). The fibrous rooting system of oil palm may have accounted for the high POM content of the soil under OL. The root tissues are of larger size and are organic materials that are yet to undergo decomposition (POM), therefore, they are subject to mineralization. The POM content of the soil under CL can be attributed to cacao's high litter production rate and slow rate of decomposition. Grasses and shrubs were mainly planted in the PL which resulted in a lower rate of litter production, even the little litter produced were eaten up by the livestock which may have contributed to its low POM. The CCL produces little litter, due to the continual use of herbicide and tillage activities associated with continuous cropping. Also, ploughing and other land pulverizing activities induce soil disturbance and expose soil organic matter to rapid decomposition (Souza et al. 2016), resulting in very low POM in the soil. This findings agrees with the results of Besnard et al. (1996) who had earlier reported a significant reduction in POM as a result of cultivation, and Kumari et al. (2011) who suggested that little soil disturbance favours the accumulation of POM. Using POM as an index for the SOM storage capacity of different land-use management systems (Sá and Lal 2009), the storage capacity of the land-use types considered in this study can, therefore, be rated as OL > CL > SFL ≥ TL > PL > CCL. However, POM represents the active pool of SOM that is easily mineralized; it has a turnover time of months to a year (Franzluebbers 2010) and may therefore not be a good indicator for carbon sequestration potential. The particulate organic matter associated with larger size aggregates was significantly higher compared to the smaller size aggregates. This agrees with the results of Besnard et al. (1996) and Kumari et al. (2011), who both reported that most of the POM they extracted were associated with the larger aggregate size. This further confirms that POM may not be a good proxy for soil carbon sequestration index. Since it has been established that carbon associated with larger size aggregates have faster turnover times (Kong and Six 2010; Schaefer et al. 2020), therefore, they are easily mineralized.

Density fractions of soil organic matter

With similar organic matter inputs, soils containing higher clay and silt contents would protect SOM more than soils containing less fine fractions (Shang et al. 2014). Thus, higher HFOM (protected form of SOM) under CL and TL can be attributed to their higher silt and clay content, and abundant availability of organic matter. This compares well with the report of Golchin et al. (1994) who recovered higher proportion of occluded fraction of organic carbon (HFOM) from soils with high silt and clay contents. It was observed that LFOM contents of the tree crop plantations and secondary forest (in the surface soil) were statistically similar, and least under cultivated land-use type. This could be due to constant soil disturbance during cultivation which exposes organic materials to the agent of decomposition (Souza et al. 2016). This is similar to the findings of Golchin et al. (1994) and Shang et al. (2014). Golchin et al. (1994) observed no significant difference in LFOM of soil under all the land-use types they considered except for cultivated land. They further reported that most of the differences in densimetric fractions of SOM were within the HFOM. Higher HFOM in the subsoil compare to corresponding LFOM can be attributed to the effect of leaching in the soil. Decomposed organic matter and exudates from root and microbes are transported down the soil profile through leaching and later trapped in the subsoil where they combine with clay particles forming organo-mineral complex such as HFOM. This corroborates the findings of Prado et al. (2016) who reported that the HFOM contents in the subsurface layer of agroforestry and extensive grazing systems were higher compared to the corresponding light fractions. Heavy fractions are organo-mineral associates having little mineralizable carbon, low reactivity, and protected from degradation (Whalen et al. 2000). The HFOM fraction is a major sink for carbon storage in soil, persists longer in soil, and is relatively stable to climate change (Poeplau et al. 2018). Thus, HFOM can be used as an index for carbon sequestration potential of the soil. The carbon sequestration capacity of the land-use types considered for this study can, therefore, be rated as follows; CL > TL > SFL > PL ≥ OL > CCL. The distribution of density fractions in the aggregate-size class implies that smaller aggregate stores SOM than the larger sized aggregates, while higher content of HFOM in 0.063-0.25 mm aggregate-size class is an indication that smaller aggregate size protects SOM than the larger sized aggregates. It can be attributed to their larger surface area with which they interact with organic compounds. This interaction is mainly by adsorption of organic matter to soil mineral phases which could be through anionic/cationic ligand exchange, cationic bridges, or weak interactions (van der Waals forces, hydrogen bonding, hydrophobic interactions, etc.) (Dignac et al. 2017). Association of small-sized soil particles (especially silt and clay particles) with SOM has been earlier reported to reduce the accessibility of decomposing agents to SOM, which lowered its turnover rate (vanVeen and Kuikman 1990). This study corroborates Oyedele et al. (2014), who suggested that smaller aggregate size protects SOM than larger aggregates. They recorded the highest SOM content in <0.05 mm aggregate-size class and lowest in the 0.25-0.5 mm aggregate-size class.

Total nitrogen of density organic matter fractions

It is not only important to know the concentrations of total nitrogen (TN) in the soil, it is also essential to know its proportions in light and heavy fractions of SOM (Prado et al. 2016). Through this, the mechanism of N availability to plants in the soil could be better understood. In all the land-use types considered for this study, the N content of HFOM was numerically higher than the corresponding LFOM. This supports earlier findings that nitrogen in the heavy fraction significantly determined total soil nitrogen (Tan et al. 2007). Song et al. (2012) reported that HFOM accounted for 89.2% of total soil N. The higher N content of HFOM under CCL in the subsoil could be attributed to the application of nitrogen-based fertilizer. Though the N content of HFOM was higher than LFOM, it is, however, the light fraction with a rapid turnover rate that contributes more to the availability of nitrogen (through mineralization and immobilization) in soil (Duxbury et al. 1989). This study revealed that the smallest aggregate-size class (0.063-0.25 mm) had the significantly highest N content in the density fractions compared to others, this could also be because the smallest aggregate class had the highest SOM content in the density fractions. This result agrees with the report of Adesodun et al. (2005) who reported higher nitrogen content in micro-aggregates (<0.25 mm) than macro-aggregates (>0.25 mm).

Carbon to nitrogen (C:N) ratio of density fractions

The rate of SOM decomposition/ mineralization is influenced by its C:N ratio. The C:N ratio of the density fractions was relatively higher in LFOM compare to HFOM, confirming the report of Sbih et al. (2012) that heavy SOM fraction has a lower C:N ratio compared to the light fraction. Higher C:N ratio in LFOM than HFOM suggests that the latter are relatively processed/mineralized SOM while the former primarily composed of less degraded plant materials (Schaefer et al. 2020). Therefore, HFOM is more stable and protected from further mineralization compared to LFOM. This is confirmed by a relatively uniform C:N ratio in HFOM among different land-use types which is similar to the findings of Tan et al. (2007). The distribution of C:N ratio in the heavy fraction of SOM across the land-use types suggests that tree crop plantations and secondary forest expectedly sequesters more carbon than continuously cultivated land. The high C:N under cacao plantation is significant and may be responsible for the usual thick layer (30-50 cm) of dry undecomposed leaves under the plantation since litters with high C:N has slower decomposition rate. However, C:N ratio is not the only factor that determines decomposition rate, other factors such as characteristics of the organic material (chemical composition, size, distribution, shoot and root branching), soil properties (soil texture and temporal variations in air and water content) and the atmosphere (evapotranspiration rates for each type of plant cover) also significantly affect decomposition rate (White 2006). Higher C:N ratio of SOM in 0.063-0.25 mm aggregate-size class suggest that SOM associated with smaller aggregates are not easily mineralized compare to those of larger aggregates. This further confirms the potential of smaller sized soil aggregates to stabilize SOM.

Conclusion

The distribution of SOM fractions was affected by land-use types in Southwestern Nigeria. Continuous cultivation significantly lowered the quantity and quality of soil organic matter compared to tree crop plantations and afforestation. This is as reflected by the lower contents of particulate organic matter (POM), light fraction organic matter (LFOM), and heavy fraction organic matter (HFOM) under arable land. This indicates that the cultivation of tree crops and afforestation stores and protects carbon in the soil. Using POM as index, the carbon storage potentials of the land-use types were: OL > CL > SFL > TL > PL > CCL; whereas the carbon protection potentials were CL > TL > SFL > PL ≥ OL > CCL when HFOM was used as index. This study showed that soil HFOM is a better index of carbon sequestration compared to either LFOM or POM. Lower C:N ratios of the HFOM than LFOM implies that the former is potentially mineralizable but are protected in soil. Higher HFOM and C:N ratio in smaller aggregates signifies the ability of the 0.63-0.25 mm sized soil aggregates to protect SOM from microbial decomposition, which is indicative of the ability of smaller sized soil aggregates to stabilize SOM.

Conclusively, tree crop plantations and secondary forest sequester carbon in the soil, and smaller-sized soil aggregate stabilizes carbon more. Thus, it is suggested that policymakers should encourage tree crops plantations and practices that stimulate soil aggregation to ensure balance between agronomic (plant nutrition) and environmental (carbon protection) considerations. Furthermore, instead of leaving the land to native fallow, cultivation of the studied economic tree crops will not negatively impact the carbon sequestration potential of the land.

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