RESEARCH ARTICLE

Organic carbon stock, carbohydrates and aggregate stability of an ultisols in managed secondary forests

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Abstract: Information on soil organic carbon stock (SOCs) and carbohydrates (R-CHO) in soils is a prerequisite to understanding the maintenance of soil health, because they promote aggregate stability, soil aeration and the amount of CO_2 in the atmosphere. The study was carried out to quantified soil organic carbon stock and acid-soluble carbohydrates in soils under different land uses in the University of Port Harcourt Research Farms and related them to maintenance of soil structural indices. The land use types were: Teak (Tectona grandis), Gmelina (Gmelina arborea), Rubber (Hevea brasilensis), and continuously cultivated plots to maize and cassava (CC). Results revealed significant changes in mean weight diameter (MWD) of water stable aggregates, acid soluble carbohydrates, and soil organic carbon storage amongst the various land use types. Mean weight diameter of the topsoil was highest in Teak (0.93 mm), followed by 0.84 mm in Gmelina soils. Acid soluble carbohydrates (R-CHO) values were 20.67, 19.80, 18.67 and 3.60 g/kg^{-1} for Rubber, Gmelina, Teak and (CC) soils, respectively. Cultivation of Teak, Gmelina, and Rubber, increased topsoil organic carbon stock by 102.8, 90.2, and 60.8% respectively, compared to the CC soil. The dry bulk density varied significantly ($p < 0.05$) in Teak at 1.28 g cm^{-3} and 1.68 g cm^{-3} in CC soils. Saturated hydraulic conductivity (Ksat) value as slow as 4.8 cm h^{-1} was obtained in CC, compared to rapid Ksat values of 25.0 and 22.6 cm h-1 in Teak and Gmelina, respectively. Relationships showed a strong positive linear correlations between MWD and SOCs (r= 0.873, $p < 0.01$) and R-CHO (r= 0.856, $p < 0.01$). A positive correlation of SOCs with macro aggregates explained the involvement of SOC stock in the stabilization of micro aggregates for the formation of macro aggregates which promotes soil aeration and capillary pores, thereby, preventing soil degradation and compaction. Therefore, integrating these forest plants into the farming systems would help in improving the structural indices of the soil and also store significant quantity of SOC.

Keywords: Bulk density, macro-aggregates, porosity, soil structure; water stable aggregates

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1 Introduction

Soil aggregates are the basic unit of the soil structure, and are related to bulk density, soil water characteristics, permeability, soil erosion, and aeration capacity. They are considered as an appropriate indicator of soil quality assessment (Bottinelli et al., 2017). A good soil structure depends on the soil aggregate size-distribution and aggregate stability. It is the most beneficial soil property for monitoring the performance soil ecosystem functions such as food production, water movement into and within the soil, and nutrient uptake by plants (Udom et al., 2024). The resistance of soil to erosion, and sequestration of organic carbon are related to soil structure and aggregate stability (Egan et al., 2018). Soil aggregate stability is an important physical indicator of soil health which protects organic matter accumulation, improves soil porosity, drainage and water availability to plants. Stable aggregates especially the macro aggregates also help in decreasing soil compaction, supports biological activity, and nutrient cycling in the soil (Okolo et al., 2020; Udom et al., 2022).

Carbohydrates (R-CHO) constitute a portion of soil organic matter that play an essential role in the maintenance and stimulation of soil microbial activities. They act as bonding agents for soil aggregates and energy sources for soil microorganisms (Cheng et al., 2015). They are involved in carbon sequestering, acting as a precursor for soil aggregation and structural stability (Gunina and Kuzyakov, 2015). Type of vegetation can change the soil physicochemical properties and microbial composition of soils, by altering microbial community structure and species composition (Shi et al., 2023). Previous studies have shown that microbial and enzymatic activity increased due to inputs of animal residues, plant litter, and root exudates (Cao et al., 2021). Various extractable forms of carbohydrates, including hot

Table 1. Characteristics of the sites used for the study

Land use	Characteristics
Continuous cropping (CC)	The area has been under continuous cropping maize and cassava for 15 years. Spent mushroom substrate and poultry manure have been used to boost soil fertility.
Gmelina (*Gmelina arborea*)	The land area is 2.96 ha with a total of 388 stands 10-year Gmelina plantation.
Rubber (*Hevea brasilensis*)	The land area is 3.5 ha with a total of 485 stands of 15-year rubber plantation.
Teak (*Tectona grandis*)	This is a 3.90 ha of 15-year Teak plantation with a total of 475 stands.

water-extractable and dilute acid-extractable carbohydrates are involved in the stabilization of soil aggregates. Studies revealed that carbohydrates are sensitive to type of vegetation and management (de Souza et al., 2016). Whereas, Ratnayake et al. (2013) reported on the positive relationships between polymeric carbohydrates, land cover type and aggregate stability of soils.

The effects of prolonged cultivation on soil organic carbon (SOC) and composition of carbohydrates have been discussed (Larré et al., 2004). They postulated that cultivation affected the proportion of soil C present as carbohydrates in the soil aggregates. However, literature showed considerable gap on the actual role of carbohydrates on aggregate stability of soils. There are several differences in opinion on the actual SOM fraction that is responsible for soil aggregation. Zhao et al. (2017) reported that organic matter fractions rather than the amount per se impacted on aggregate stability of the soil. Whereas, Duchicela et al. (2013); Guo et al. (2018) and Guo et al. (2019); found a direct correlation between liter volume, total SOM content and aggregate stability. Anaya and Huber-Sannwald (2015); Martins et al. (2012) observed that carbohydrate (R-CHO) pool was not effective in stability of soil aggregates, whereas, Lykhman et al. (2020) found that R-CHO was involved in aggregate stability in the presence of humified SOM pool.

Other studies observed that due to the temporary biological stability and rapid degradation of carbohydrates, their long-lasting role in soil aggregation differed in certain soil conditions, (Parwada and Van, 2016; Yılmaz et al., 2019). Carrizo et al. (2015) found that differences in plant cover, soil characteristics, types of extractable carbohydrates (cold or hot water or acid-hydrolyzed) influenced micro-and macro-aggregate stability of soils. Zubair et al. (2012) observed that carbohydrates extracted by hot water and dilute acid were suitable indicators for soil quality assessment, particularly in relation to soil aggregation.

The effects of different tree species on water stability of aggregates and carbohydrate content remain relatively understudied, limiting our understanding of their roles in shaping the soil health and ecosystem services such as their roles in water holding capacity and protection of soil aggregates fro disruption. In this study we seek to address certain caps in knowledge on the amount of organic carbon and carbohydrates stored in the topsoil of continuous cultivated soils compared with some trees vegetation such as Teak (Tectona grandis), Gmelina (Gmelina arborea), and Rubber (Hevea brasillensis).

2 Materials and Methods

2.1 The study location

The experiment was carried out at the Arboretum in the Faculty of Agriculture Teaching and Research Farm (4°54' N, 6°55' E), and a rubber plantation within the University of Port Harcourt (4°54' N, 6°54' E). The area is of the Tropical rainforest belt, with mean annual precipitation of 2,436 mm (Amaechi et al., 2014). Some characteristics of the study sites are shown in Table 1.

2.2 Soil sampling and analysis

Soil samples were collected at 0-15 cm depth in four replicates, each from: Teak (Tectona grandis), Rubber (Hevea brasillensis), Gmelina (Gmelina arborea), and compared with a continuously cultivated cassava/maize intercropped (CC). Samples were labeled and stored in polyethene bags for laboratory analyses. The bulk samples were air-dried at room temperature, sieved through 2.0 mm mesh, while soil samples for water stable aggregates were sieved through 4.75 mm sieve. Aggregate stability was determined using the wet-sieving method (Kemper and Rosenau, 1986). The percentage of resistant aggregates on each sieve size, representing water stable aggregates (WSA) was calculated as:

$$WSA = MR/MT \times 100$$

where MR is the mass of resistant aggregates (g) and MT the total mass of wet-sieved soil (g). The mean weight diameter (MWD) of the water stable aggregates was calculated by the following equation (Hillel, 2004):

$$MWD = \sum_{i-1}^{n} xiwi$$

where is the mean diameter of each size fraction, and wi is the weight of aggregates in each size range as a fraction of the dry weight of the soil sample.

Total carbohydrate (R-CHO) in the soil was measured by weighing 120 mg of the soil samples into stoppered test tubes and 0.5 ml of 12 ML^{-1}Sulphuric acid was added. After hydrolysis for 16 h at room temperature, 12 ml of water was added and heated for 8 hours. 0.5 ml of the each of the hydrolysate was mixed with 0.5 ml of distilled water and 1 ml of 5% phenol solution and 5 ml of concentrated sulphuric acid was added to the solutions. Carbohydrate-C standards (0, 0.2, 0.4, 0. 6, and 0.8 ppm) were prepared using glucose. The carbohydrates were measured at 485 nm wavelength (Safarik and Santruckova, 1992).

Saturated hydraulic conductivity (Ksat) was measured by Reynolds et al., (2002) method and calculated by rearranging Darcy's equation for constant head condition as below;

$$Ksat = \frac{V}{AT} x \frac{L}{\Delta H}$$

Where, V is the volume of water collected at steady state (cm^3), L is the length of the soil core (cm), A is the cross-sectional area (cm^2), T is the time (h) and H is the hydraulic head difference (cm). Total organic carbon (CT) was determined using acid dichromate wet-oxidation procedure (Nelson and Sommers, 1996). Organic carbon storage was calculated from the equation (Poeplau et al., 2017) as:

$$C \text{ stock } (\text{kg m}^{-2}) = \sum p \times SOC \times BD \times (1-CP)$$

where: p is the thickness of the soil layer (m), SOC is the organic carbon concentration of layer (g kg^{-1}), BD is the bulk density of the soil layer (kg m^{-3}), and CP is the percentage of coarse particles of soil layer.

The disturbed bulk soil samples were air-dried and passed through 2 mm sieve to separate gravel from fine earth, and used to measure particle-size distribution by the hydrometer method as described by Gee and Bauder (1986). Dry bulk density was measured on oven-dried soil core samples by the method of Grossman and Reinsch (2002) as:

$$Bulk\ density = \frac{Mass\ of\ oven-dried\ soil\ (g)}{Volume\ of\ bulk\ soil\ (cm^3)}$$

Total porosity was measured with the method of Flint and Flint (2002) and calculated as:

$$Total\ porosity = \frac{Volume\ of\ water\ at\ saturation\ (cm^3)}{Volume\ of\ bulk\ soil\ (cm^3)}$$

2.3 Data Analysis

Statistical analyses were performed using the SAS Software (S.A.S., 1996). Analysis of variance was performed, followed by multiple comparisons. Means were separated according to the least significant difference (LSD) of Fishers' protected test. A significant correlation coefficient was tested at 5% probability.

3 Results and Discussion

3.1 Total carbohydrates, soil organic carbon storage, and permeability

Total carbohydrates (R-CHO), soil organic carbon storage and permeability of the soil are presented in Table 2. The results showed that total carbohydrates were significantly influenced by land use ($P < 0.05$). The highest R-CHO value of 20.67 g kg^{-1} was found Rubber plantation soil at 0-15 cm depth, followed 19.80, 18.67, and 3.60 g kg^{-1} in Gmelina, Teak and the continuous cultivated soils, respectively (Table 2). Soil organic carbon storage has the lowest value in the continuously cultivated soil at 31.8 kg m^{-2} compared to significant $p < 0.05$) higher values of 55.7, 55.4, and 54.4 kg m^{-2} found in Teak, Rubber, and Gmelina soil, respectively. Saturated hydraulic conductivity (Ksat) was significant at 25.0 and 22.6 cm h^{-1} in Teak and Gmelina soils, respectively, ($p<0.05$), compared with very slow value 4.8 cm h^{-1} obtained for the continuous cultivated (CC) soil. Water permeability was very rapid for Teak and Gmelina, rapid for Rubber, and very slow for CC soils (Table 2). Water holding capacity of the soil showed higher values for Teak, Rubber, and Gmelina (0.26, 0.25, and 0.21 g g^{-1}), respectively, compared 0.19 g g^{-1} found in CC soil.

Table 2. Total carbohydrates, soil organic carbon storage, hydraulic conductivity and water holding capacity of 0-15 cm topsoil under different land use

Land use	R-CHO (g kg^{-1})	SOCS (kg m^{-2})	Ksat (cm h^{-1})	WHC (g g^{-1})	Permeability class
Teak	18.67b	55.7a	25.0a	0.26a	Rapid
Rubber	20.67a	55.4a	16.2b	0.21b	Moderately
Gmelina	19.80ab	54.7a	22.6a	0.25a	Rapid
CC	3.60c	31.8b	4.8c	0.19b	Very slow

Means followed by the same alphabet within column are not significantly different at p<0.05. R-CHO - total carbohydrates, SOCS – soil organic carbon stock, Ksat- saturated hydraulic conductivity, WHC- water holding capacity, control- continuously cultivation

The significant increase in total carbohydrates (R-CHO) in Rubber, Gmelina, and Rubber soils can be used to explain this vegetation's role in enriching the soil with carbohydrates, and can suggest an improvement in soil aggregation under these plants. On the other hand, the very low R-CHO content in continuous cultivated soil can also explain to the negative influence of cultivation on soil carbohydrates and possible effects on soil structural degradation Earlier studies (John et al., 2005), reported that complex polysaccharide in SOM had the ability to bind inorganic soil particles into stable aggregates. However, other findings had differed in the conclusion that carbohydrates cannot always be considered as persistent structural stabilizers because of their rapid degradation by microbial activity (Udom and Simon, 2020). In this study, the increase in saturated hydraulic conductivity (Ksat) and water holding capacity (WHC) in Teak, rubber and Gmelina soils in contrast to the continuous cultivated soil further suggest improvement in macro aggregate structure (Ye et al., 2019).

The mean values of soil organic carbon storage (SOCS) in Teak, Rubber and Gmelina could give significant indication of atmospheric C sequestrated in their ecosystem It can be concluded that heavy matter from the tree plants increased carbon storage in soils which further improved the soil bulk density, water stable aggregates and saturated hydraulic conductivity. This assertion is consistent with previous reports of Lan et al., 2021; Udom and Ogunwole, 2015) tend to differ in opinions of Cao et al. (2021) studies on till and no-till experiment. Incorporation of Teak, Rubber or Gmelina into farming systems can benefit the soil with the amount of R-CHO which to improve the macro aggregates and the amount of water retained in the soil for plant use, while the amount of SOC stored help in regulating the atmospheric carbon in the soil environment.

3.2 Water stable aggregates and other physical properties of the soil

Water stable aggregates and related physical properties of the soils are shown in Table 3 and Table 4. The results indicate significant impact of the plants on water stable aggregates and mean weight diameter (MWD) (Table 3), and similar changes on dry bulk densities and total porosity Table 4). Water stable aggregates (WSA) in 4.75 - 2.0 mm size class was a low as 8% in continuous cultivated plot. Whereas, macro aggregates > 2.0 mm for Teak, Gmelina, and Rubber were 15.5, 14.0, and 13.5%, respectively. Water stable aggregates WSA 0.5 - 0.25 mm was significantly lower in Gmelina soil at 18.0% ($p<0.5$). In general, macro aggregates > 0.25 mm were 62.0, 47.5 and 47.5% in Teak, Gmelina and Rubber soil, respectively at 0-15 cm depth. Micro aggregates <0.25 mm were generally higher in all the soils except in Teak with a value of 38%. Aggregates stability measured by the mean weight diameter (MWD) in Table 3 showed significant differences with land uses, which Teak soil has the highest MWD of 0.93 mm, followed by Gmelina (0.84 mm) and Rubber soil with 0.79 mm at 0-15 cm depth. In general, the MWD values indicated dominance of less erodible aggregates in soils under tree plants.

The effect of different land use on water-stable of aggregates (WSA) and mean weight diameter (MWD) in this study explained the extent of enhancement of soil agglomeration under the influence of different land cover. The significant increase of macro-aggregate greater than 2.0 mm in Teak, Gmelina and Rubber compared to continuous cultivated soil showed that quality of soil organic matter (SOM) produced from tree plants improved formation of larger aggregates. This result further corroborate the assertion of Zhao et al. (2018) that quality and quantity of SOM in forest ecosystem

Table 3. Water stable aggregates and aggregate stability of the 0-15 cm topsoil under different land use

Land use	Aggregate sizes (mm)					MWD (mm)
	4.75-2.0	2.0-1.0	1.0-9.5	0,5-0.25	<0.25	
Teak	15.5a	7.5a	14.5a	24.5a	38.0b	0.93a
Rubber	13.5a	4.5b	7.0b	22.5a	52.5a	0.79ab
Gmelina	14.0a	7.5a	8.0b	18.0b	52.5a	0.84a
CC	8.0b	7.0a	8.5b	24.5a	52.0a	0.66b

Means followed by the same alphabet within column are not significantly different at p <0.05. CC- continuously cultivation, MWD- mean weight diameter

Table 4. Particle-size distribution, bulk density and total porosity of soil under the different land use at 0-15 cm depth

Land use	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Textural class	Bulk density (g cm^{-3})	Total porosity (%)
Teak	780	100	120	SL	1.28b	51.7a
Rubber	778	102	120	SL	1.37b	48.3b
Gmelina	780	100	120	SL	1.38b	47.9b
CC	790	110	100	SL	1.68a	36.6c

Means followed by the same alphabet within column are not significantly different at p<0.05. B.D- bulk density, T.P- total porosity, control- continuously cultivated cassava and maize plot, SL- sandy loam

were responsible for the production of macro-aggregates and stable structures in some tropical sandy loam soils. Aggregate stability, expressed by the MWD had a significant proportion of macro-aggregates greater than 0.5 mm produced in Teak soil, which is consistent with the findings of Liu et al. (2022) and Zhang et al. (2016) who found that organic residues added to the soil through litter falls increased production of macro-aggregates greater than 2.0 mm and concomitant larger MWD of water stable aggregates.

In Table 4, the soil is sandy loam at 0-15 cm depth, and showed a non-significant difference in silt and clay fractions under the various land uses (pβ0.05). Bulk density values ranged between 1.28 g cm^{-3} in Teak to 1.68 g cm^{-3} in continuous cultivated (CC) soil. The percent total porosity was significant ($p<0.05$) in Teak, Rubber, and Gmelina with values of 51.7, 48.3, and 47.9%, respectively, compared to lower value of 33.6%, found in CC soil. There was no speculation that the particle-size distribution would vary significantly in this study, because according to Akamigbo (1984) earlier report in accuracy of field textures in the humid tropics, found that land use had insignificant influence to alter the soil texture. The CC increased in sand content and decreased SOM can be adduced to the high bulk density and low total porosity found in the soil (Udom and Ogunwole, 2015). Whereas, the built-up of SOM in Teak, Rubber and Gmelina soils improved soil bulk density, and increased total porosity.(Zhaoa et al., 2017)

Table 5. Relationships amongst some structural properties of the soil

Dependent	Independent	Equation	R^2	R	P
MWD	SOCS	Y = 0.420 +0.167x	0.762	0.873	**
MWD	R-CHO	Y = 0.617 + 0.012x	0.733	0.856	**
MWD	Ksat	Y = 0.60 + 0.122x	0.769	0.877	**
WHC	MWD	Y = -0.08 + 0.19x	0.297	0.535	ns
Ksat	R-CHO	Y = 0.12 + 0.12x	0.828	0.910	**
Ksat	SOCS	Y = -1.51 + 1.38x	0.806	0.898	**
SOC	Clay	Y = -5.78 + 0.95x	0.557	0.746	*
Micro-aggregates < 0.25 mm	SOCS	Y = 2.08 + 1.19x	0.437	0.461	ns
Macro-aggregates > 0.25 mm	R-CHO	Y = 2.84 + 0.54x	0.569	0.754	*

R^2- Coefficient of determination, R- correlation coefficient, MWD- mean weight diameter, SOCS- soil organic carbon storage, R-CHO- total carbohydrates, WHC- water holding capacity, Ksat- saturated hydraulic conductivity, * significant at $p<0.05$, ** significant at $p <0.01$, ns- non significant at $p>0.05$

3.3 Relationships amongst Related Soil Properties

Relationship among soil properties revealed a significant (p<0-01) positive linear correlation between MWD and R-CHO, accounting for 73.3% of the relationship (Table 5). A highly significant positive correlation was found between MWD and SOCS (R = 0.873, p<0.01), which explained 76.3% of the positive variation. There was also a significant positive correlation between MWD and Ksat (R = 0.877, p<0.01), accounting for 76.9% of the positive variation. A highly significant positive correlation between Ksat and (R-CHO) and Ksat and SOCS at (R = 0.828, p<0.01), and (R = 0.806, p<0.01) showed that both SOCS and R-CHO influenced the saturated hydraulic conductivity (Ksat). Micro-aggregates less than 0.25 mm in diameter showed a non-significant relationship with SOCS.

The positive linear correlation of MWD with SOC and Total carbohydrates (R-CHO) confirmed the positive roles of SOC and R-CHO as aggregating agents when in association with soil aggregates (Zubair et al., 2012; Lan et al., 2021). Similarly, the positive correlation between MWD and Ksat confirmed the crucial role of SOC in relation to the structural stability of soil and to a large extent, the aeration capacity and water relationship in the soil. The involvement amount of SOC storage in the stabilization of macro-aggregates was found in positive correlations of SOCS with macro-aggregates, consistent with the report of Ratnayake et al. (2013), and Wang et al., (2022). The model Y = 0.420+0.167x for MWD and SOCS, and Y = 0.617+0.012x for MWD and R-CHO can be used to predict the influence of SOC and R-CHO on aggregate stability and consequently the structural behavior of soils. This conclusion can also be tested in the model Y = 2.84+0.54x, for macro-aggregates > 0.25 mm and R-CHO.

4 Conclusions

Conclusion drawn from this study are that plantation trees reduced bulk density, increased total porosity, saturated hydraulic conductivity and formation of macro-aggregates > 0.25 mm.in diameter. Continuous cropping increased sand content with negative impact on bulk density and water stability of aggregated. There was evidence of structural deformation of the soil due to continuous cropping as indicated by the large proportion of micro-aggregates < 0.25 mm. Total carbohydrates and SOCS showed a significant positive correlation with the MWD. A linear model showed that SOC stock controlled saturated hydraulic conductivity (Ksat), while the total carbohydrates content modified the macro-aggregates greater than 0.25 mm.

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