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# ENUMERATION OF CARBON AND NITROGEN CONTENTS OF WATER-STABLE AGGREGATES IN LAYERS OF TOPSOILS FROM CULTIVATED AND ADJACENT BUSH-FALLOW LOAMY SOILS

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## ABSTRACT
***Soil organic carbon (SOC) and total soil nitrogen (TSN) dynamics have both pedological and agronomic basis. Knowledge of their retention within aggregate hierarchies of varying soil textures as influenced by land use change is limited. The capacity of loam (L), clay loam (CL), sandy loam (SL) and sandy clay loam (SCL) soils to retain SOC and TSN in water-stable aggregate (WSA) at 10-cm intervals of 0-30 cm topsoil depths under cultivated and bush-fallow/uncultivated systems was investigated. The soils showed high dispersion ratio and great variations in aggregate silt and clay indices (CL > L > SCL > SL) under both land uses. Across soil depths, the uncultivated CL, SL and SCL soils had moderate to high > 2.00 mm WSA whose reduction due to cultivation impact was more pronounced in SL than in CL soil. Across soil depths and land uses, SOC content seemed higher in the macro- (> 0.50 mm) than in the micro- (< 0.50 mm) aggregates of all the soils while the reverse marked aggregate TSN content in almost all the soils. Cultivation mostly reduced macro-aggregate-associated SOC and TSN in L > CL > SL and in L > SL > CL > SCL soils, respectively. However, cultivation showed no reduction influence on micro-aggregate-associated SOC of all the soils. Cultivation-related reduction in micro-aggregate-associated TSN was more pronounced in the generally more 'clayey' CL and SCL than the L and SL soils. So, the potential of bush-fallowing to enhance micro-aggregate-associated TSN storage and stabilization against adverse influence of cultivation depends on soil texture.***

**Key words:** uncultivated soil, macro- and micro- aggregates, land use

## INTRODUCTION
Soil organic carbon (SOC) and total soil nitrogen (TSN) are dynamic soil components that vary widely among soil types and land uses. This is so because organic carbon (C) and nitrogen (N) contents in cropland are strongly influenced by the quantity of C inputs, cropping intensity, soil and crop management practices (Rahman, 2013). Intensive cultivation of agricultural land contributes enormously to reduced SOC and TSN contents (Adesodun *et al*., 2007; Rahman, 2010) but fallow management system is reported to promote soil aggregate stability and thus stabilize aggregate SOC and TSN (Mtali-Chafadza *et al*., 2020). As important determinants of soil quality, SOC and TSN need to be conserved, and their conservation is essential to long-term sequestration of C and N, and overall soil productivity. Increased SOC content improves soil structure and sustainability and enhances crop yield and productivity. However, SOC depletion has been associated with reduced soil aggregation and structural stability with attendant susceptibility to accelerated erosion in most tropical soils (Lal, 1991; 2019; Blanco-Canqui and Benjamin, 2013; Liu *et al*., 2019)

Bush fallow has traditionally been recognized as an efficient, balanced and sustainable agricultural system for improving soil organic matter (SOM), soil productivity and fertility restoration in the tropics (Ramakrishnan, 1984; Schlecht and Buerkert, 2004; Ayoola and Adeniyan, 2006; Nhantumbo *et al*., 2009). Long fallow period of 5-8 years often promotes SOM and build-up of plant macro-nutrients in the soil (Salako *et al*., 1999). However, due to increasing population, economic changes and land fragmentation challenges, the length of fallow periods in producing fields has shortened to 4-5 years (Ramakrishnan, 1984; Ogban *et al*., 2004). The importance of fallow in agricultural sustainability relates to changes in soil physiochemical properties as influenced by fallow systems (bush fallow, forest fallow, improved fallow, bare fallow, etc), fallow duration (short, medium and long terms), soil types and agro ecological regions. Salako *et al*. (1999) reported that 1-3 years' fallow periods substantially enhanced soils aggregate stability irrespective of the fallow system. Conversely, Mtali-Chafadza *et al*. (2020) found no difference in soil nutrients accumulation with different fallow periods.

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Unlike fallow system, cultivation has been associated with deterioration in soil aggregate structure due to soil disturbances that destroy aggregates, expose encapsulated SOC to microbial processes and increase its vulnerability to decomposition and erosion (Adesodun *et al*., 2007; Lal, 2019). Hence, cultivation leads to reduction in amount and stability of macro-aggregates but not micro-aggregates (Tisdall and Oades, 1982). Soil susceptibility to structural degradation increased with years of cultivation (Shepherd *et al*., 2001). Differences in preferential accumulation of SOC and TSN in aggregate fractions also vary under different land use systems (Shrestha *et al*., 2007; Liu *et al*., 2019). Adesodun *et al*. (2007) found higher aggregate SOC and TSN in large macro-aggregates (4.76-2.0 mm) under uncultivated soils, and in micro-aggregate (< 0.25 mm) under cultivated soils. The influence of cultivation on SOC loss as affected by soil texture and soil depth has also been reported. Okebalama *et al*. (2017) found that loss of C pool in different soil textures was higher at 0-10 cm top surface layer than the lower soil depths (10-20 and 20-30 cm). Also, Campbell and Souster (1982) reported high losses of C on sandy soils, while Saggar *et al*. (2001) found that percentage C losses from silt loam soil was 1.5 times higher than from silty clay loam.

Most often, SOC and TSN components, as well as soil structure, are often altered through soil management practices (Bronick and Lal, 2005). Conversion of fallow land to agricultural cultivated land has been shown to alter soil structural and chemical characteristics (Salako *et al*., 1999; Adesodun *et al*., 2007). Due to the dynamic nature of SOC and TSN in soil aggregates, precise evaluation of the effect of bush-fallow and cultivation on soil aggregate stability in relation to aggregate SOC and TSN is imperative for maintaining soil physical and chemical fertility in agroecosystems. Such assessment could also be useful for developing long-term and process-based strategies for improving and sustaining biodiversity in managed ecosystems. Information from the study can help farmers and land users to manage soils in a sustainable manner.

Although aggregate C and N contents in relation to aggregate stability under different management systems have been assessed (Puget *et al*., 2000; Adesodun *et al*., 2007; Onweremadu *et al*., 2007, Shrestha *et al*., 2007), there is limited research on the capability of different soil textures to retain C and N in water stable aggregates (WSA) following cultivation of erosive susceptible soils of the humid tropics. The extent to which short fallow (4-5 years) could influence C and N stabilization in aggregate hierarchies of varying soil textures against adverse environmental processes associated with cultivation is still unknown. Our study assessed soil aggregate stability in water, as well as the storage and distribution of aggregate-associated SOC and TSN in four different soil textural types at 10 cm segmental layer of the topsoil (0-30 cm) under cultivated and uncultivated land uses. Recognizing the important role of finer soil particles in soil aggregation, the study therefore hypothesized that change in landuse would induce greater macro-aggregate (> 0.50 mm) associated SOC and TSN losses in sand dominated than in clay or silt dominated textured soils.

## MATERIALS AND METHODS

### The Study Locations and Environment

Soils used in this study were collected from locations at Awgu, Okigwe and Nsukka I and II, in Southeastern Nigeria. Awgu is located at 5º43´N and 7º21´E; Okigwe at 5º28´N and 7º32´E, and Nsukka I and II between 6º52´N and 6º41´N and 7º24´E and 7º17´E. Figure 1 shows the relative positions of the study areas in Southeastern Nigeria. Climate of the study area is humid tropical with average annual bimodal rainfall of about 1700 mm and annual temperature of 26ºC (Climate-Data, 2021). The underlying geology of Nsukka is mainly Sandstone, whereas Awgu and Okigwe are of Shale origin (Jungerius, 1964; Orajaka, 1975; Onyewuchi and Ugwu, 2017). Nsukka and Okigwe are of hilly terrain while Awgu is more of a flat land. Detailed description of individual locations, soil classification, and land-use history of the fields is presented (Table 1).

Soil samples were collected from these locations having different soil textures to ensure variability of these soil parameters. From each location, soils were sampled from two different land uses (cultivated and adjacent bush-fallow/uncultivated farmlands) at three successive depths (0-10, 10-20 and 20-30 cm), giving six samples per location. Soils were sampled up to 30 cm depth because tillage practice in the study area did not exceed 30 cm soil depth. The selection of cultivated and uncultivated farmlands was aimed at ensuring variability in aggregate stability of the soils since we assumed that soil physiochemical properties were altered upon change in land use. Generally, the farmlands are indiscriminately established by local farmers at no definite pattern.

### Soil Analysis

The collected soil samples were air-dried and divided into two portions. A portion sieved with 4.75 mm mesh was used for aggregate size separation while the other 2.00 mm sieved portion was used for soil physiochemical determinations. Aggregate size separation was performed by wet sieving (Elliot, 1986). Using a nest of four sieves (2.00, 1.00, 0.50 and 0.25-mm mesh), a 100 g of the < 4.75 mm soil sample was weighed into the topmost sieve and submerged in water at room temperature for 5 min. The sieves were vertically oscillated 50 times in a water oscillation machine in about 2 min. Thereafter, the WSA retained on each sieve (> 2.00, 1.00-2.00, 0.50-1.00, 0.25-0.50, and < 0.25 mm) were oven-dried at 40ºC, and

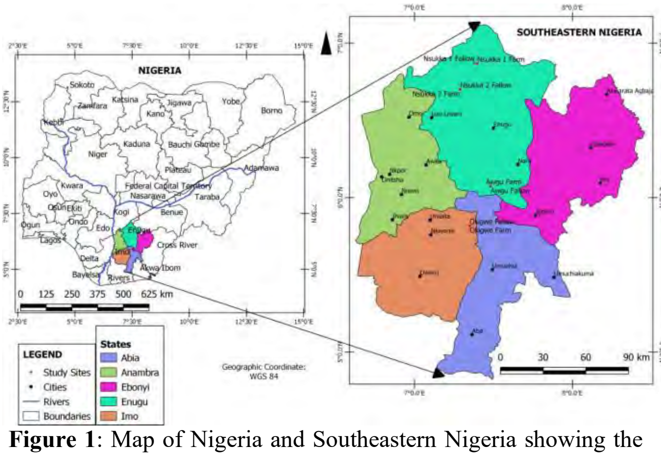


**Figure 1**: Map of Nigeria and Southeastern Nigeria showing the study locations

**Table 1:** Study sites description, soil classification and land-use history

| Location/soil classification | Land use | Cropping system and Predominant vegetation | Tillage practice/land use history |
|---|---|---|---|
| Awgu (Typic Paleudult) | Cultivated farmland | Cassava monocropping without soil amendment | Field was manually tilled with hoes after 5 years bush-fallow |
| | Uncultivated field | Plantain, banana, mango and oil palm trees | Five years bush-fallow field |
| Okigwe (Typic Hapludult) | Cultivated farmland | Cassava, yam and maize intercrop without fertilizer application; Mulching with harvested maize stover and weed residues | Field was manually tilled with hoes after a 5-year bush-fallow |
| | Uncultivated field | Oil palm, orange and oil bean trees, including *Mimosa pudica, Panicum maximum, and Pennisetum purpureum* grasses | Five-year bush-fallow agricultural field |
| Nsukka I (Typic Kandiustult), (Nkpologu series) | Cultivated farmland | Under a 3-year continuous cultivation of sorghum - soybean intercrop with application of swine and poultry droppings at 15 Mg ha$^{-1}$ and 90 kg ha$^{-1}$ NPK 15:15:15 fertilizer | Field was conventionally tilled for three consecutive years after a 4-year bush-fallow |
| | Uncultivated field | Scattered gmelina trees and shrubs, *Panicum maximum, Cyperus esculentus, Spermacoce verticillata,* and *Cynodon nlemfuensis* grasses | Research field under a 4- year bush-fallow |
| Nsukka II (Typic Paleustult), (Uvuru series) | Cultivated farmland | Cassava, maize, yam and fluted pumpkin mixed-cropping with application of poultry manure | Field was conventionally-ridged across the slope |
| | Uncultivated field | Scattered plantain, oil palm, gmelina trees. *Mimosa pudica, Andropogon gayanus,Oldenlandia corymbosa,Guterbergia* spp. | Four years bush-fallow agricultural land |

Adapted from Okebalama *et al*. (2017)

then weighed and used to determine aggregate SOC and TSN. The mass of aggregates > 0.25 mm was calculated by subtracting the sum of the oven-dried weights of materials retained on each sieve from the air-dried weight of the original sample. The proportion of each aggregate class in the total sample weight was thus computed as the ratio of its oven-dry weight (uncorrected for sand) to the weight of the material (100 g) before sieving.

Particle size analysis of < 2.00 mm soil fractions was done by hydrometer method (Gee and Bauder, 1986), using calgon as dispersant. Deionized water alone was used to determine water dispersible clay (WDC) and water dispersible silt (WDSi). The micro-aggregate stability indices of the soils including clay dispersion index (CDI), dispersion ratio (DR), aggregated silt and clay (ASC) and clay flocculation index (CFI) were calculated as follows (Igwe *et al*., 1999):

$$CDI = [\%\ clay\ (water) / \%\ clay\ (calgon)] \times 100 \quad (1)$$

$$DR = [\%\ silt + \%\ clay\ (water)] / [\%\ silt + \%\ clay\ (calgon)] \quad (2)$$

$$ASC = [\%\ clay + \%\ silt\ (calgon)] - [\%\ clay + \%\ silt\ (water)] \quad (3)$$

$$CFI = [\%\ clay\ (calgon) - \%\ clay\ (water)] / [\%\ clay\ (calgon)] \times 100 \quad (4)$$

Soil pH was measured in 1:2.5 soil to water suspensions using a pH meter. The SOC concentration in the whole soil (< 2.00 mm) and in the various WSA fractions were determined by Walkley and Black wet oxidation method (Nelson and Sommers, 1982), and SOM computed by multiplying the OC by the Van Bemmelen factor of 1.724. The macro-Kjeldahl digestion method using $CuSO_4$ and $Na_2SO_4$ catalyst mixture as described by Bremner and Mulvaney (1982) was used for the determination of total N concentration in WSA fractions. Cation exchange capacity (CEC) was determined by the $NH_4OAC$ pH 7 method (Thomas, 1982).

### Statistical Analysis

Data were descriptively analyzed using Microsoft Excel 2016 to estimate population mean and percent coefficient of variation. Line graphs and column charts were used to show relationships and distributions of measured parameters amongst the soil textures and across soil depths and land uses.

## RESULTS

### Physiochemical Properties of the Soils

The particle size distribution of soils as presented in Table 2 show wide distribution in the content of soil separates; particularly the silt content, which ranged from 3 to 49% with a CV of 77% across soil depths and land uses. Percent silt content in Awgu was two-times more than that in Okigwe, and four-times more than that in Nsukka I and II. Also, percent silt content declined with soil depth in Awgu and Okigwe cultivated soils while percent clay content tended to increase with soil depth in almost all the locations and under both land uses. Accordingly, Okigwe soil had moderate clay and sand particles while Nsukka I and II soils had more of sand than clay and silt particles. Across land uses, the textural classes which also varied slightly with soil depth in all the locations except at Nsukka II, mainly included clay (C), loam (L), clay loam (CL), sandy loam (SL) and sandy clay loam (SCL) at 0-30 cm.

Across land uses and soil depths, the micro-aggregate stability indices of the soils (Table 3) show that the clay dispersion index (CDI) was between 25.16 and 63.59, with a mean of 44.08 and a CV of 28%. However, the degree of variation in CDI was slightly more under the cultivated (30.78%) than the uncultivated (25.30%) land use. As such, highest CDI was obtained in SCL (46.28%) and CL (53.72%) soils under cultivated and uncultivated land uses, respectively. Across land uses, CDI was maximal at 0-10 cm depth in L and CL soils, but minimal at the same depth in SCL soil. Except in uncultivated CL soil showing decreased CDI values with soil depth, the CDI followed no distinct trend with soil depth for the other soils in both land uses. Dispersion ratio (DR) values averaged 0.71 with a low CV of 13%; aggregated silt and clay (ASC) and water dispersible silt (WDSi) values show wide variations with an average of 12.72 (CV = 51%) and 19.17 (CV = 56%), respectively. As such, maximum ASC and WDSi values were obtained in CL and L textured soils, respectively. High CV (33%) was observed with WDC, which ranged from 6.48 to 20.48; wherein the maximum value of between 10.48 and 20.48 was obtained in CL soils across soil depths and land uses.

**Table 2:** Particle size distribution and textural classification of the soils under cultivated and uncultivated land uses

| Location | Soil depth (cm) | % Clay | % Silt | % Sand | Textural class |
|---|---|---|---|---|---|
| | | | Cultivated | | |
| Awgu | 0-10 | 17 | 49 | 34 | Loam |
| | 10-20 | 27 | 39 | 34 | Loam |
| | 20-30 | 31 | 23 | 46 | Sandy Clay Loam |
| | Mean | 25 | 37 | 38 | |
| Okigw | 0-10 | 27 | 23 | 50 | Sandy Clay Loam |
| | 10-20 | 43 | 15 | 42 | Clay |
| | 20-30 | 47 | 9 | 44 | Clay |
| | Mean | 39 | 16 | 45 | |
| Nsukka | 0-10 | 16 | 9 | 76 | Sandy Loam |
| | 10-20 | 22 | 7 | 72 | Sandy Clay Loam |
| | 20-30 | 22 | 7 | 72 | Sandy Clay Loam |
| | Mean | 20 | 8 | 73 | |
| Nsukka | 0-10 | 26 | 7 | 68 | Sandy Clay Loam |
| | 10-20 | 26 | 9 | 66 | Sandy Clay Loam |
| | 20-30 | 30 | 5 | 66 | Sandy Clay Loam |
| | Mean | 27 | 7 | 67 | |
| | % CV | 34 | 86 | 28 | |
| | | | Uncultivated | | |
| Awgu | 0-10 | 27 | 39 | 34 | Loam |
| | 10-20 | 31 | 25 | 44 | Clay Loam |
| | 20-30 | 27 | 29 | 44 | Loam |
| | Mean | 28 | 31 | 41 | |
| Okigw | 0-10 | 17 | 25 | 58 | Sandy Loam |
| | 10-20 | 31 | 25 | 44 | Clay Loam |
| | 20-30 | 43 | 13 | 44 | Clay |
| | Mean | 30 | 21 | 49 | |
| Nsukka | 0-10 | 14 | 11 | 76 | Sandy Loam |
| | 10-20 | 21 | 8 | 72 | Sandy Clay Loam |
| | 20-30 | 25 | 10 | 66 | Sandy Clay Loam |
| | Mean | 20 | 10 | 71 | |
| Nsukka | 0-10 | 26 | 3 | 72 | Sandy Clay Loam |
| | 10-20 | 28 | 7 | 66 | Sandy Clay Loam |
| | 20-30 | 22 | 7 | 72 | Sandy Clay Loam |
| | Mean | 25 | 6 | 70 | |
| | % CV | 28 | 71 | 25 | |
| | Grand %CV | 31 | 77 | 26 | |

The soil pH ranged from 4.5 (strongly acidic) to 5.9 (moderately acid) across the soil textures and land uses, with a mean of 5.2 and CV of 6% (Figure 2). A large variation (42%) in SOM content was observed across soil depths and land uses, with maximum (4.22%) and minimum (0.67%) values in the CL and SL soils, respectively (Figure 3). Except in L soil, SOM decreased with soil depth in all the uncultivated soils and in cultivated CL and SCL soils. The CEC of soils ranged from 7.2 to 27.60 cmol$_c$ kg$^{-1}$ with a CV of 44% across soil depths and land uses (Figure 4). However, the CEC mean values under the cultivated and uncultivated land uses was 21.20 cmol$_c$ kg$^{-1}$ with a CV of 18%, and 9.50 cmol$_c$ kg$^{-1}$ with a CV of 20%, respectively.

### Water-Stable Aggregate Fractions of the Soil Textural Types

Results of Table 4 show great variation (CV > 54%) in the proportions of WSA amongst soils textures, across soil depths and land uses. Pooled over soil depths, the proportion of > 2.00 mm WSA in SCL, CL, L and SL soils was 79.25%, 53.04%, 20.71% and 18.89%, respectively, in the cultivated land; and 78.85, 66.07, 6.77 and 49.38%, respectively, under the uncultivated land use. The > 2.00 mm WSA of the soil textural types decreased with increasing soil depth in both land uses; except in the uncultivated L and SCL soils with no definite trend. More so, reduced proportions of > 2.00 mm WSA with concomitant increase in almost < 2.00 mm WSA fractions at 0-30 cm depth was observed in the cultivated soils of CL and SL than their uncultivated counterpart.

### Soil Organic Carbon Concentrations in Water-Stable Aggregates

With CV > 30%, the aggregate SOC of the soils as presented in Figure 5 showed ranges of 0.38-2.01%, 0.57-1.74%, 0.37-1.14%, and 0.53-1.48% in the L, CL, SL and SCL soils, respectively, across WSA fractions, soil depths and land uses. The SOC concentrations in almost all of the WSA fractions decreased with increasing soil depth in the cultivated and uncultivated CL soils and in the uncultivated L soil. Maximum concentration of SOC at 0-10 cm across WSA fractions was observed in all the soils, except in the cultivated L and SCL soils. The aggregate SOC distribution in SCL soil was greater at 10-20 > 0-10 > 20-30 cm soil depth. Pooled over soil depths, all the soils textural types generally show elevated SOC concentrations in macro-aggregates (> 0.50 mm) than in micro-aggregates (< 0.50 mm). However, macro-aggregate associated SOC (> 0.50 mm WSA) were more in the uncultivated than the cultivated soils of L and CL textures, whereas the reverse was obtained with SCL soil. The macro-aggregate-associated SOC concentrations in SL soil were comparable under both land uses; except in the 1.00-2.00 mm WSA fraction which contained reduced SOC under the cultivated than the uncultivated land use. Further, the micro-aggregates associated SOC concentration in the L, CL and SL soils were comparable under both land uses, but increased more in the cultivated than in the uncultivated SCL soil.

**Table 3:** Micro-aggregate stability indices of the soils under cultivated and uncultivated land uses

| Soil texture/ | Depth (cm) | CDI | DR | % ASC | CFI | % WDC | % WDSi |
|---|---|---|---|---|---|---|---|
| | | | | Cultivated | | | |
| Loam | 0-10 | 51.46 | 0.76 | 16.00 | 48.54 | 8.48 | 41.28 |
| | 10-20 | 32.02 | 0.76 | 16.00 | 67.98 | 8.48 | 41.28 |
| | 20-30 | 47.51 | 0.78 | 12.00 | 52.49 | 14.48 | 27.28 |
| Clay Loam | 0-10 | 77.34 | 0.60 | 20.00 | 22.66 | 20.48 | 9.28 |
| | 10-20 | 29.38 | 0.52 | 28.00 | 70.62 | 12.48 | 17.28 |
| | 20-30 | 26.85 | 0.57 | 24.00 | 73.15 | 12.48 | 19.28 |
| Sandy Loam | 0-10 | 41.12 | 0.70 | 7.28 | 58.88 | 6.48 | 10.56 |
| | 10-20 | 48.16 | 0.74 | 7.28 | 51.84 | 10.48 | 10.56 |
| | 20-30 | 38.97 | 0.74 | 7.28 | 61.03 | 8.48 | 12.56 |
| Sandy Clay Loam | 0-10 | 40.68 | 0.77 | 7.28 | 59.32 | 10.48 | 14.56 |
| | 10-20 | 56.21 | 0.73 | 9.28 | 43.79 | 14.48 | 10.56 |
| | 20-30 | 41.94 | 0.85 | 5.28 | 58.07 | 12.48 | 16.56 |
| | Mean | 44.30 | 0.71 | 13.31 | 55.70 | 11.65 | 19.25 |
| | %CV | 30.78 | 13.64 | 56.29 | 24.48 | 32.30 | 59.40 |
| | | | | Uncultivated | | | |
| Loam | 0-10 | 54.68 | 0.79 | 14.00 | 45.32 | 14.48 | 37.28 |
| | 10-20 | 34.38 | 0.82 | 10.00 | 65.62 | 10.48 | 35.28 |
| | 20-30 | 39.58 | 0.82 | 10.00 | 60.42 | 10.48 | 35.28 |
| Clay Loam | 0-10 | 63.59 | 0.62 | 16.00 | 36.41 | 10.48 | 15.28 |
| | 10-20 | 54.07 | 0.64 | 20.00 | 45.93 | 16.48 | 19.28 |
| | 20-30 | 43.50 | 0.57 | 24.00 | 56.50 | 18.48 | 13.28 |
| Sandy Loam | 0-10 | 47.09 | 0.70 | 7.28 | 52.91 | 6.48 | 10.56 |
| | 10-20 | 48.16 | 0.81 | 5.28 | 51.84 | 10.48 | 12.56 |
| | 20-30 | 48.45 | 0.73 | 9.28 | 51.55 | 12.48 | 12.56 |
| Sandy Clay Loam | 0-10 | 25.16 | 0.74 | 7.28 | 74.85 | 6.48 | 14.56 |
| | 10-20 | 37.75 | 0.67 | 11.28 | 62.25 | 10.48 | 12.56 |
| | 20-30 | 29.78 | 0.60 | 11.28 | 70.22 | 6.48 | 10.56 |
| | Mean | 43.85 | 0.71 | 12.14 | 56.15 | 11.15 | 19.09 |
| | %CV | 25.30 | 12.63 | 45.38 | 19.76 | 34.50 | 54.66 |
| | Grand %CV | 27.59 | 12.86 | 50.76 | 21.74 | 32.72 | 55.85 |

CDI - clay dispersion index, DR - dispersion ratio,
ASC - aggregate silt and clay, CFI - Clay flocculation index,
WDC - water dispersible clay, WDSi - water dispersible silt

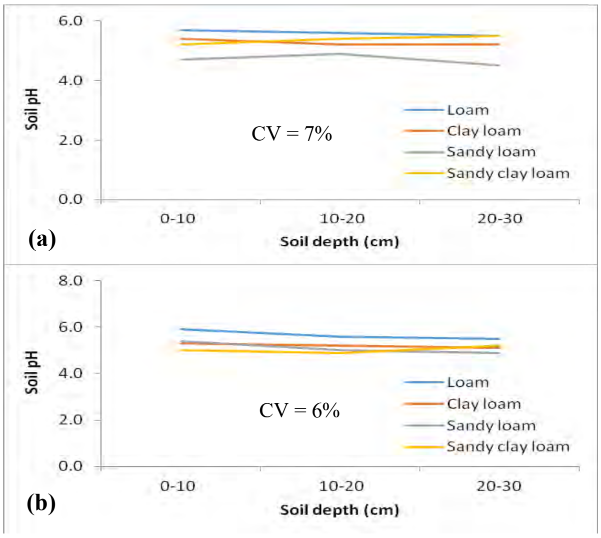


**Figure 2:** Soil pH of the different soils under cultivated (a) and uncultivated (b) land uses

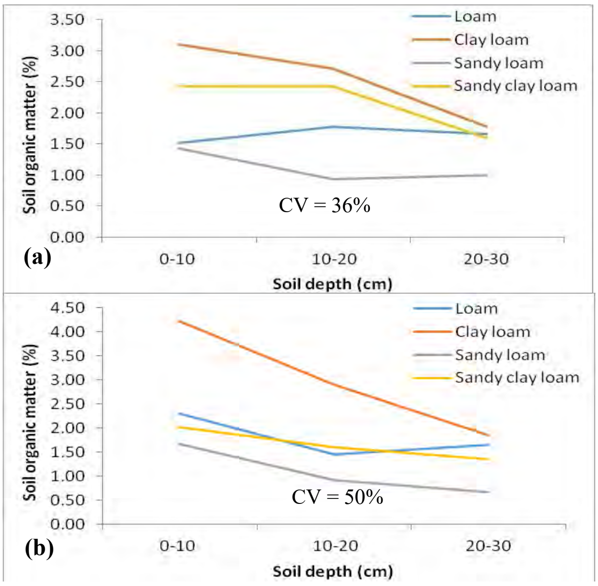


**Figure 3:** Soil organic matter content of the soils under cultivated (a) and uncultivated (b) land uses

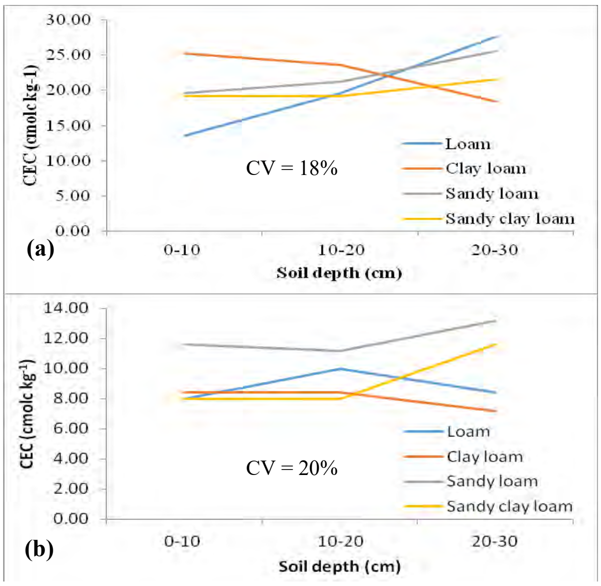


**Figure 4:** Cation exchange capacity (CEC) of the soils under cultivated (a) and uncultivated (b) land uses

**Table 4:** Percentages of water-stable aggregates of the soils under cultivated and uncultivated land uses

| Land use/ soil texture | Depth (cm) | Water-stable aggregates (mm) > 2.00 | 1.00-2.00 | 0.50-1.00 | 0.25-0.50 | < 0.25 |
|---|---|---|---|---|---|---|
| | | Cultivated | | | | |
| Loam | 0-10 | 46.15 | 13.47 | 10.34 | 10.22 | 19.82 |
| | 10-20 | 8.78 | 12.88 | 16.57 | 24.55 | 37.22 |
| | 20-30 | 7.19 | 27.68 | 23.50 | 17.32 | 24.33 |
| Clay | 0-10 | 65.69 | 13.22 | 6.47 | 5.18 | 9.44 |
| Loam | 10-20 | 52.70 | 19.86 | 11.21 | 5.56 | 10.67 |
| | 20-30 | 40.73 | 19.96 | 17.60 | 11.59 | 10.12 |
| Sandy | 0-10 | 19.67 | 30.52 | 21.83 | 11.41 | 16.57 |
| Loam | 10-20 | 18.80 | 32.20 | 26.17 | 10.39 | 12.44 |
| | 20-30 | 18.21 | 29.28 | 29.06 | 10.15 | 13.30 |
| Sandy | 0-10 | 73.86 | 6.80 | 5.43 | 4.02 | 9.89 |
| Clay | 10-20 | 83.37 | 6.56 | 2.18 | 1.53 | 6.36 |
| Loam | 20-30 | 80.52 | 5.35 | 4.51 | 3.92 | 5.70 |
| | Mean | 42.97 | 18.15 | 14.57 | 9.65 | 14.66 |
| | %CV | 65.86 | 54.40 | 62.87 | 66.70 | 60.87 |
| | | Uncultivated | | | | |
| Loam | 0-10 | 3.01 | 7.79 | 11.87 | 19.57 | 56.76 |
| | 10-20 | 2.84 | 22.36 | 21.50 | 11.50 | 41.80 |
| | 20-30 | 14.47 | 21.03 | 20.53 | 14.86 | 29.11 |
| Clay | 0-10 | 74.40 | 9.96 | 5.23 | 2.61 | 7.80 |
| Loam | 10-20 | 67.35 | 11.19 | 5.85 | 2.95 | 12.66 |
| | 20-30 | 56.47 | 16.32 | 12.78 | 5.35 | 9.08 |
| Sandy | 0-10 | 84.11 | 4.46 | 3.65 | 3.41 | 4.37 |
| Loam | 10-20 | 32.89 | 25.26 | 22.56 | 12.59 | 6.70 |
| | 20-30 | 31.15 | 37.58 | 17.21 | 7.67 | 6.39 |
| Sandy | 0-10 | 89.16 | 4.96 | 1.20 | 0.92 | 3.76 |
| Clay | 10-20 | 73.46 | 13.12 | 5.42 | 2.24 | 5.76 |
| Loam | 20-30 | 73.92 | 9.10 | 4.78 | 3.37 | 8.83 |
| | Mean | 50.27 | 15.26 | 11.05 | 7.25 | 16.09 |
| | %CV | 63.19 | 63.98 | 69.94 | 82.62 | 106.78 |

## Total Soil Nitrogen Concentrations in Water-Stable Aggregates

The aggregate TSN range from 0.11-0.34%, 0.11-0.48%, 0.06-0.28%, and 0.08-0.39% in the L, CL, SL and SCL soils, respectively, across WSA fractions, soil depths and land uses (Figure 6). The CV amongst aggregate TSN fractions was between 29% and 38%. With few exceptions, TSN concentrations across soil depths increased as the WSA fractions decrease, thus indicating more TSN in the micro-aggregates than macro-aggregates in CL and SCL soils. In the CL soils, while TSN concentration across WSA fractions at 0-10 cm depth was more under the uncultivated (0.20-0.36%) than cultivated (0.14-0.34%) land use, the uncultivated land (0.34-0.36%) had more TSN in < 0.50 mm than the cultivated land (0.22-0.34%). Pooled over soil depths, the macro-aggregate-associated TSN was more in the uncultivated than cultivated soils of L and SL textures. Accordingly, more micro-aggregate-associated TSN under the cultivated than uncultivated land characterized the L and SL soils; the reverse was obtained in CL soil.

## C/N Ratio in Water-Stable Aggregates of the Soils

The C/N ratios of various WSA classes were generally low and varied greatly (CV > 30%) amongst the soils and across soil depths in both land uses (Figure 7). Across land uses, the obtained C/N values ranged from 1.77-10.50, 1.69-9.14, 1.79-10.67 and 2.22-11.36 in the L, CL, SL and SCL soils, respectively. While the trend in aggregate C/N distribution with soil depth and land uses appears undefined amongst the soil textures, the CL soil mostly show maximum C/N values at 0-10 cm depth across WSA fractions in both land uses.

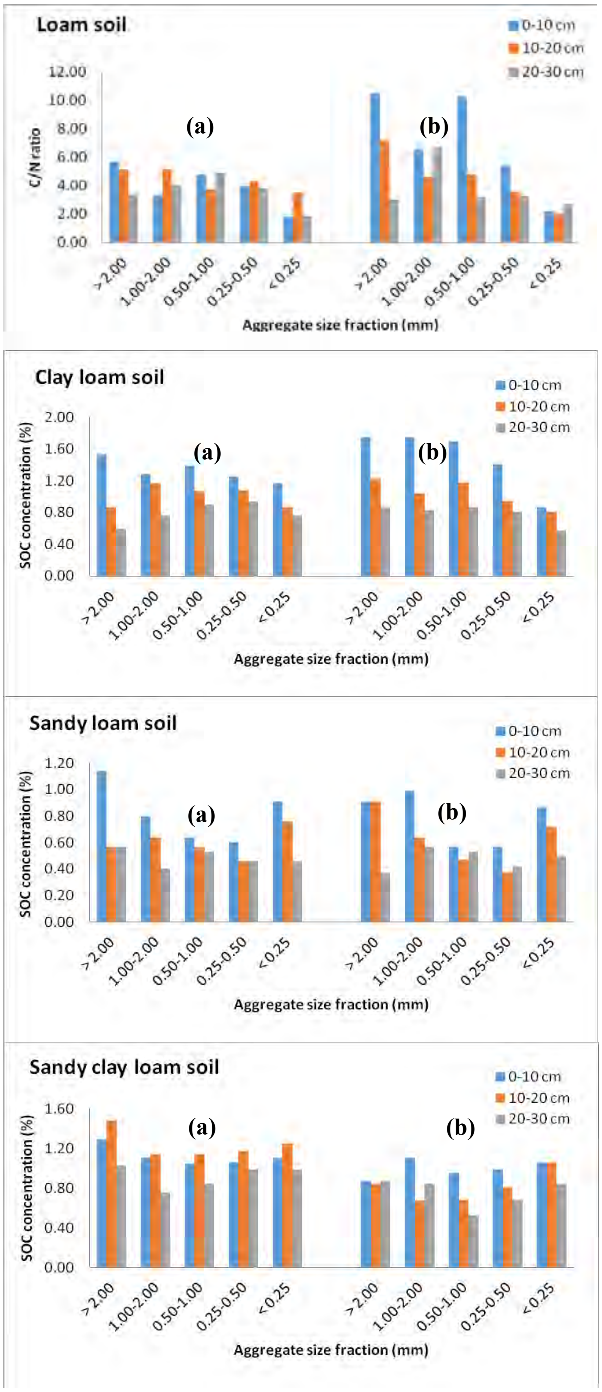


**Figure 5:** Aggregate soil organic carbon (SOC) concentrations under cultivated (a) and uncultivated (b) land uses

## DISCUSSION

### Physicochemical Properties of the Soils

The clay distribution within the soil depth indicated some form of eluviation and illuviation processes that had occurred within the soils. The more pronounced reduction in percent silt content with depth in the cultivated soils of Awgu and Okigwe could be related to deposition of silty materials through flooding or from mudflows or by river; and secondly, eluviation and illuviation processes move clay from the topsoil (hence increase in silt content) and deposit it in the subsoil (reduction of silt content). The comparatively high silt content in Awgu and Okigwe soils may be because the soils originated from the same parent material (Orajaka, 1975; Onyewuchi and Ugwu, 2017). However, the high silt content in Awgu soil was mainly attributed to deposition of silt materials from a nearby river (Okebalama *et al*., 2017). The dominance of sand particles (> 66%) across the soil depths and land uses is typical of the Sandstone parent material at Nsukka (Edeh *et al*., 2015). Possibly, these soils could be characterized as having better air and water permeability and hence enhanced drainage. Based on the content of the soil separates at 0-30 cm depth and for ease of evaluating the influence of soil texture on measured parameters, the studied soils were herein referred to as L, CL, SL and SCL, for Awgu, Okigwe, Nsukka I and II locations, respectively.

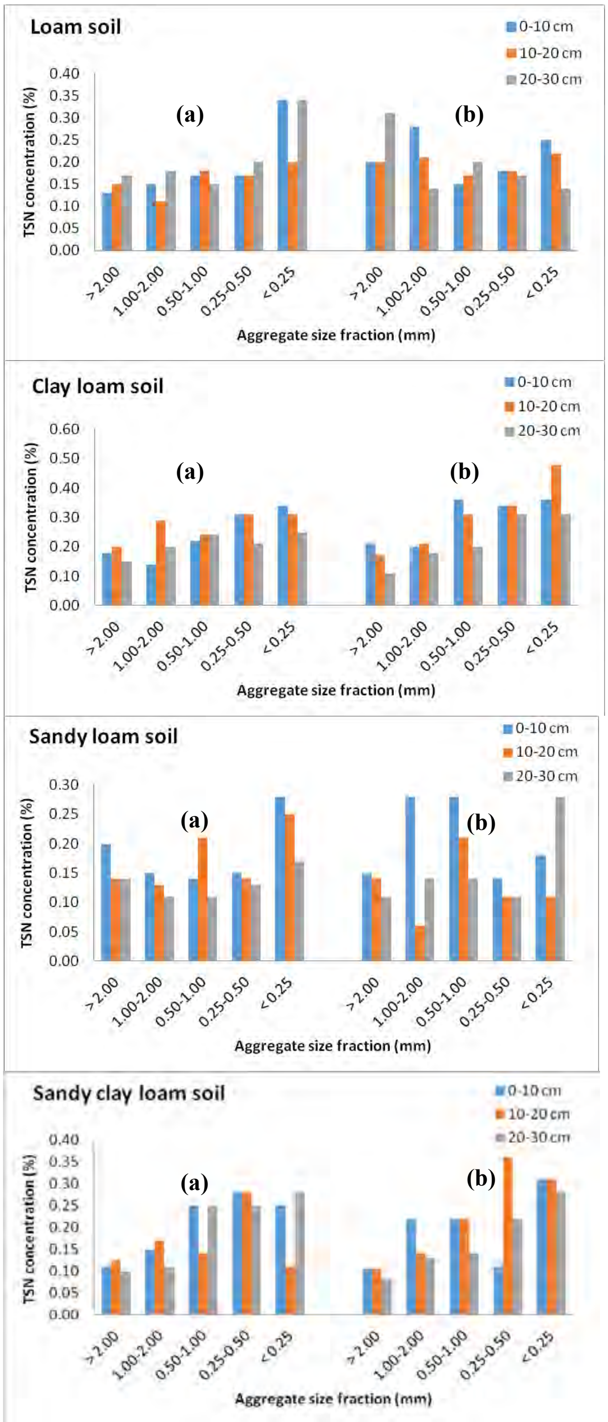


**Figure 6:** Aggregate total soil nitrogen (TSN) concentrations under cultivated (a) and uncultivated (b) land uses

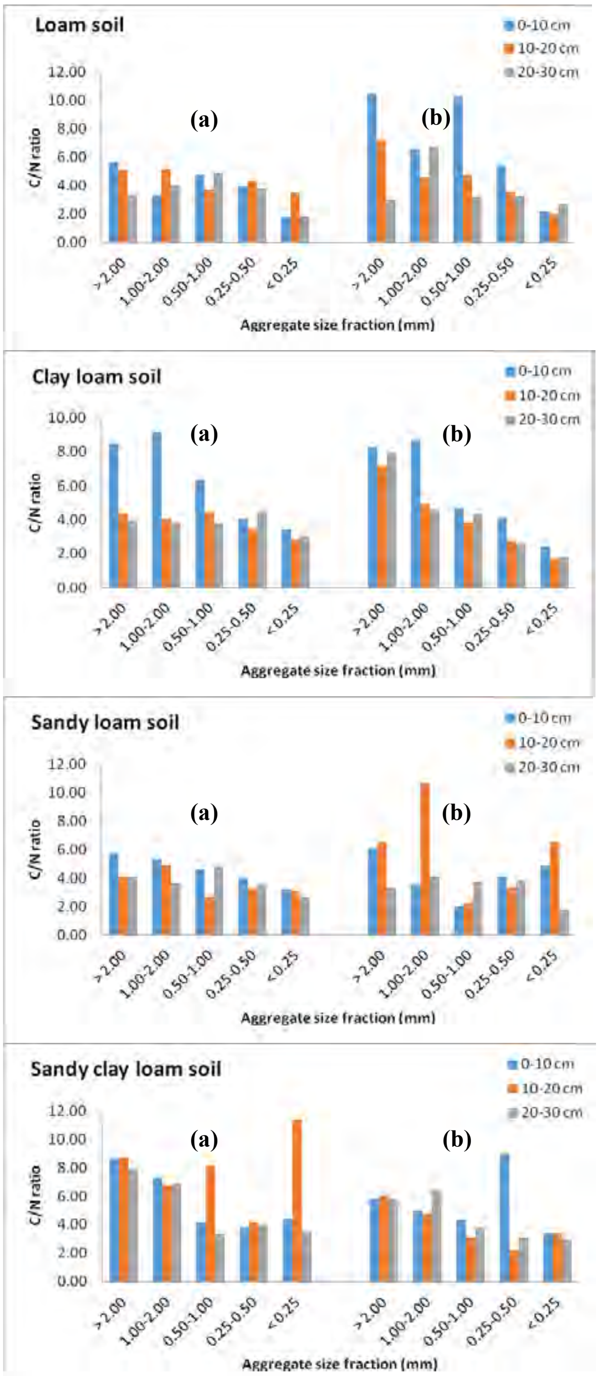


**Figure 7:** Aggregate C/N ratio of the soils under cultivated (a) and uncultivated (b) land uses

All the determined micro-aggregate indices are important estimates of soil stability and dispersibility in water because of their significant in estimating the susceptibility of soil to water erosion (Igwe and Obalum, 2013; Zhu *et al*., 2018; Ahukaemere *et al*., 2021). High values of CFI and ASC imply better stability while high DR and CDI values indicate lower stability (Igwe *et al*., 1999; 2009). The low ASC and high DR values under both land uses suggest that the soils were structurally weak and instable in water. Similar observation in coarse textured soils as reported by Igwe and Udegbunam (2008) indicate that soils with high DR can easily erode. However, the moderate CDI and CFI show that the soils were moderately stable and less dispersive in water. Igwe *et al*. (1995) opined that CFI, amongst other aggregate indices, could better predict potential soil erodibility in some soils of southeastern Nigeria. Also, the low WDC and WDSi values indicating less dispersibility (Zhu *et al*., 2018) suggest that these soils may be less erodible despite the high rainfall regime of the study environment. Regarding the high variation in WDSi and WDC, the relatively high WDSi of the L soil resulted from its high silt content, while the relatively high WDC of the CL soil could be linked to high clay content as compared to the other soils. It is thus important to note the critical role of clay in aggregate stability of the soils. This could be ascribed to the inherent susceptibility of clay-rich soils since clay upon wetting swells, slakes or disperses.

The low pH of the soils was within the pH range of most acidic soils of the humid tropics (Igwe and Udegbunam, 2008; Agim *et al*., 2019). The pH of the soils was moderately acid, except the pH of the cultivated SL soil which falls within the strongly acidic range. The strongly acid pH could be linked to tillage (due to cultivation) which promoted leaching of base cations, leaving dominance of $H^+$ in the topsoil. This may have contributed to the low OM content of the SL soils in both land uses. In a similar manner, Igwe (2005) attributed low SOC contents of a strongly acid cultivated SL soil to severe leaching and inter-rill erosion due to high rainfall intensity.

The low SOM is common to the soils of the study area known for low fertility status (Anikwe, 2010; Obalum and Obi, 2010; Agim *et al*., 2019). The comparatively high SOM contents of the CL soils than the other soils under both land uses could be due to its high clay content, which enhanced soil aggregation via binding of SOM to soil minerals, and subsequent reduction in SOM oxidation and losses. The increased SOM content in the 0-10 cm depth was attributable to addition of organic matter from plant biomass and associated increased activity of soil microorganisms in decomposition and preservation of organic matter. More so, reduced erosion and surface runoff losses due to vegetation cover may contribute to increase in SOM at 0-10 cm depth. The organic materials were decomposed, redistributed and stored in successively layers within the soil profile, thus showing reduced concentration of SOM with soil depth as found in the uncultivated CL, SL and SCL soils. Such a decline in SOC concentration shows the effect of short-term fallow on the accumulation and segmental distribution of OC at intervals of 10 cm within the topsoil layer. The result buttresses the importance of segmental computation of topsoil SOC in soil science research (Kumar *et al*., 2013; Okebalama *et al*., 2017). The improvement in SOM content of the cultivated SCL soil could be linked to the effect of applied poultry manure. Addition of poultry droppings on SCL soil increased SOC following first time cultivation of a two-year bush-fallow field (Okebalama *et al*., 2020).

The CEC of the soils were generally low, conceivably due to the inherent acid pH and low SOM content of the soils. Also, excessive precipitation contributes to considerable loss of basic cations through leaching and replacement of the exchange sites with acid cations (Igwe *et al*., 1999). The CEC of the soils are not different under each landuse, though the CEC of the cultivated soil is more than the uncultivated soils. This finding contradicts the report of reduced exchangeable cations concentrations following change in land use (Adesodun *et al*., 2007; Schweizer *et al*., 2017).

### Differences in Water-Stable Aggregates with Soil Textures and Land Uses

The L soil under both land uses exhibited high rate of > 2.00 mm aggregate instability in water, attributable to the high WDSi index of the soil. The CL and SCL soils had comparatively moderate to high stability of the > 2.00 mm aggregates across soil depth and land uses. This observation could be due to the differences in clay content, SOM and parent material. Clay and oxides of Fe and Al are predominant aggregating agents in tropical soils (Igwe *et al*., 2013). Despite having originated from similar parent material as SCL, the cultivated SL soil exhibited high > 2.00 mm aggregates instability in water while the stability of the > 0.50 mm macro-aggregates in SCL soil was not influenced by cultivation processes. Adesodun *et al*. (2007) reported a decrease in > 0.50 mm WSA of two SCL soils due to cultivation. In comparing WSA of cultivated and adjacent forested soils in Nigeria, Spaccini *et al*. (2001) found a significant reduction in > 1.00 mm macro-aggregate fractions of cultivated SCL and SL soils and concluded that cultivation had a lower impact on sandy than clayey soil.

Cultivation related increase in micro-aggregates of the cultivated SL soil which was created from the > 2.00 mm macro-aggregates disintegration, could be explained by three possible reasons which are i) effect of reduced soil pH (strong acidity) on aggregate stability; ii) low SOM content; and iii) frequent soil disturbance (conventional tillage) within the three-year continuous land cultivation. Igwe and Udegbunam (2008) found that soil pH, SOC, including clay and silt contents among others affects water-dispersible properties of Ultisols. Low soil pH affects microbial population and their capacity to produce organic compounds that promotes soil aggregates stabilization (Castro Filho *et al*., 2002). Six *et al*. (1999) recognized the importance of SOC in macro-aggregate formation because it provides energy for microbes that are responsible for soil aggregation. Blanco-Canqui and Benjamin (2013) also reported decrease in aggregate stability with SOC decrease. Puget *et al*. (2000) found that macro-aggregates are more sensitive than micro-aggregates in responding to changes in land use and adverse cultivation processes. Accordingly, the maximal > 2.00 mm aggregates reduction at 0-30 cm depth in the cultivated SL than cultivated CL soils suggests that the formation of stable micro-aggregates within macro-aggregates was impeded due to loss of intra-particulate OM during aggregate turn over. Nonetheless, the study results indicate that cultivating SL and CL soils reduced the > 2.00 mm WSA to smaller fractions.

The reduced stability of the > 2.00 mm WSA with increased soil depth followed similar trend with the SOM concentration but trailed inversely with the percentage clay content of the CL and SL soils. This implies that the formation and stability of > 2.00 mm aggregates was mainly controlled by SOM content, thus confirming that macro-aggregation depends on SOM (Boix-Fayos *et al*., 2001). In view of that, though high clay and SOM contents marked CL and SCL soils, they had comparatively low micro-aggregates (< 0.50 mm) compared to that in the L and SL soils. It thus suggests that clay particles and SOM may be contributing to macro-aggregation (> 0.50 mm) in CL and SCL soils.

### Soil Organic Carbon Concentration in Water-Stable Aggregates

The low aggregate SOC concentrations of the soils could be linked to decreased plant biomass inputs, increased SOM decomposition because of high temperature regime and increased soil erosion/runoff and leaching losses due to the high rainfall that prevails in the study environment (Igwe, 2005; Igwe *et al*., 2009; 2013). The decline in aggregate SOC concentration with increased soil depth indicates the positive effect of bush-fallow and the capacity of the uncultivated L and CL soils to promote OC storage in successive soil layers. In contrast to CL soils, this pattern was not maintained in the cultivated L soil probably because of the nature of the soil which predisposes it to structural degradation and subsequent SOC loss following cultivation processes. Land use type affects the amount and quality of litter input, litter decomposition rates and the processes of OM stabilization in soils (Shepherd *et al*., 2001). The maximal aggregate SOC at 0-10 cm depth which cut across the soil textural types; except in the cultivated L and SCL soils, connotes high OC accumulation and preservation due to enriched influx of organic material and slow breakdown and mineralization. The relatively high aggregate SOC at 10-20 cm compared to 0-10 cm in the cultivated SCL soil suggests cultivation related SOC loss, exacerbated by severe erosion and runoff due to the hilly terrain of the site.

The preferential maximal accumulation of SOC in macro-aggregates in all the soils under both land uses, except in the cultivated L soil is similar to the reportedly higher SOC in large macro-aggregates (4.76-2.0 mm) under uncultivated soil (Adesodun *et al*., 2007). High accumulation of SOC in macro- than micro- aggregates could be explained by the aggregate C/N ratio which decreased with decrease in WSA fractions. This indicates that microbial alteration of SOM was more associated with the micro-aggregates than the macro-aggregates. The impact of land use change on SOC storage of the soils at 0-30 cm depth was more on the macro- than the micro- aggregate. According to Puget *et al*. (2005), macro-aggregate associated SOC is mostly labile with faster turnover rates as compared to micro-aggregate associated SOC.

The influence of cultivation in reducing macro-aggregate associated SOC concentration in the L, CL and SL soils indicate the susceptibility of these soils to SOC losses upon change in landuse. Notably, the macro-aggregate associated SOC loss at 0-30 cm depth in the > 2.00, 1.00-2.00, and 0.50-1.00 mm WSA fractions amounted to 112%, 108% and 35%, respectively, in the L soil; and 28%, 12% and 12%, respectively, in the CL soil. With 20% SOC loss in the 1.00-2.00 mm fractions of the SL soil, the susceptibility of the soils to macro-aggregate associated SOC loss was more in the L > CL > SL textured soils. This implies higher SOC loss in silt-, and clay- than in sand-dominated soil. On the contrary, Spaccini *et al*. (2001) found that decreased macro-aggregate associated SOC as influenced by soil texture was generally greater in sandy than clayey soils. Feller and Beare (1997) reported that soil aggregation, texture and mineralogy control SOC storage in macro-aggregates while Kumar *et al*. (2013) stated that the residence time of aggregate associated SOC determines its storage and stabilization in soils. In this study, the cultivation-related reduction in macro-aggregate associated SOC may have resulted from soil disturbance which disaggregated the aggregates and increased oxidation of exposed SOM by microbes, thus exacerbating C loss through erosion/runoff and emission to the atmosphere. Research findings in confirmation to this abound in the literature (Follett, 2001; Spaccini *et al*., 2001; Wright and Hons, 2005).

Despite the reduced stability of the > 2.00 mm aggregates in cultivated SL soil, the influence of cultivation on SOC loss was limited to the 1.00-2.00 mm fractions. Even so, the somewhat comparable SOC concentrations of the other aggregate fractions under both land uses suggest that the soil is rather not inclined to SOC losses upon land use change. This could be ascribed to the positive effect of the three-year fertilizer application which might have promoted aggregate SOC storage such that the frequent soil disruption due to conventional tillage did not inhibit the formation of stable micro-aggregates within macro-aggregates of > 2.00 and 0.50-1.00 mm (Six *et al*., 1998). Similarly, the improved aggregate SOC which cuts across almost all the WSA fractions, soil depths and land uses of SCL soil is attributable to the positive effect of poultry manure input used in crop cultivation. This indicates the capability of SCL to conserve SOC in cultivated land.

The non-reduction in micro-aggregate associated SOC of all the cultivated soils supports that SOC was more stabilized in micro-aggregates (Bayer *et al*., 2000). Such effectual SOC preservation implies that the cultivation processes had no negative effect on micro-aggregate associated SOC. The short-term bush-fallow seems to have improved SOC stabilization in micro-aggregate fractions, as this appears to be independent of the soils' textural types. Micro-aggregates retain SOC in a way that is comparatively less susceptible to physical disturbance (Puget *et al*., 2000). The association of SOC to silt-and clay-size fractions maintains a strong link to mineral particles, thereby forming OM-mineral complexes (Khanday *et al*., 2017). Moreover, the confinement of OC in the core of soil micro-aggregates with long mean residence time makes it inaccessible to microbial decomposition (Laird, 2001). This essential mechanism explains the involvement of the soil micro-aggregates in both C and N sequestration.

**Total Soil Nitrogen Concentrations in Water-Stable Aggregates**

The TSN concentrations in various WSA fractions of the soils, across soil depth and land uses were generally low. The low aggregate TSN concentration of the soils could be linked to low pH of the soils which probably reduced microbial activities and retarded nitrification of OM (Jiang and Bakken, 1999). Perhaps, replacing bush-fallow with improved-fallow which incorporates planting leguminous crops on fallowed agricultural abandoned fields could increase the N content and consequently, boost C build up in the soils. Knops and Tilman (2000) observed that the rate of C accumulation in agricultural abandoned fields was controlled by the rate of N accumulation, which in turn depends on atmospheric N deposition and symbiotic N fixation by legumes. Notably, the aggregate-associated TSN was relatively high in the CL soil compared to the L and SL soils. This could be explained by the differences in SOM mineralization in the micro-aggregates of these soils. The higher micro- than macro-aggregate-associated TSN in the CL and SCL soils under both land uses is similar to Agim *et al*.'s (2019) observation in SCL soil, but differs with the findings of Adesodun *et al*. (2007) who reported greater TSN in > 2.0 mm and < 0.25 mm aggregates under uncultivated and cultivated SCL soils, respectively.

Aggregate TSN distribution with soil depth was not consistently similar amongst the study soils. The maximal accumulation of aggregate TSN of uncultivated CL soils at 0-10 cm depth suppose that the bush-fallow period probably enhanced N stabilization in the various WSA fractions. Ironically, the influence of cultivation on CL soil resulted to between 6 and 63% aggregate TSN losses, with greater loss by the macro- than the micro aggregates. At 0-30 cm depth, the improved TSN concentrations in > 1.00 mm WSA under cultivated landuse was possible due to N addition from the decomposed residue biomass used as mulch. Nevertheless, cultivation-related reduction in micro-aggregate associated TSN concentrations amounted to 19-27% in the < 0.50 mm by the CL soil and to about 41% in the < 0.25 mm WSA by the SCL soil. Conversely, the improved micro-aggregates associated TSN as recorded in the cultivated L and SL soils suggest that these soils are capable of promoting N storage and preservation in micro-aggregates. Hence, the impact of short-term bush-fallow on micro-aggregate associated TSN conservation in cultivated systems is dependent on soil textures.

Cultivation induced reduction in macro-aggregate associated TSN affected all the soil textural types at 0-30 cm depth. Consequently, 24% TSN loss was recorded in the 0.50-1.00 mm WSA fraction (CL), whereas 14% loss of TSN was obtained in the 1.00-2.00 mm WSA fractions (SCL). Greater macro-aggregate associated TSN losses as obtained in the L textured soil amounted to 58%, 43% and 4% in the > 2.00, 1.00-2.00 and 0.50-100 mm WSA fractions, respectively. However, in the SL textured soil, losses were 23% and 37% in the 1.00-2.00 mm and 0.50-1.00 mm WSA, respectively. It therefore indicates that L and SL soils were most susceptible to cultivation related macro-aggregate SOC loss as compared to CL and SCL soils. Over all, the susceptibility of the soils to macro-aggregate associated TSN loss was greater in the L > SL > CL > SCL soils. It thus implies that the 4 to 5 years bush fallow period enhanced stabilization of macro-aggregate associated TSN in the CL and SCL more than in L and SL soils.

## CONCLUSIONS

Soil aggregate stability and the distributions of SOC and TSN in WSA of the studied soil textures across soil depths and under both land uses are heterogeneous. The stability of the > 2.00 mm aggregates at 0-30 cm depth under both land uses is comparatively high in CL and SCL and low in L and SL soils. All the soil textural types are capable of storing more SOC in macro- than micro- aggregate at 0-30 cm depth under both land uses. However, cultivation related SOC reduction mostly affects the macro- but not the micro- aggregates in these soils. Accordingly, the macro-aggregates associated SOC losses at 0-30 cm depth was greater with L > CL > SL soils. Aggregate TSN of the uncultivated CL soil is subject to losses due to cultivation influence, with greater loss in the macro- than the micro- aggregates. Across soil depths, high micro- than macro- aggregate associated TSN characterized L, CL, SL and SCL of the cultivated soils. However, only the cultivated L and SL soils are capable of micro-aggregates associated TSN conservation and improvement. At 0-30 cm depth, reduction in macro-aggregate associated TSN concentrations was more pronounced in the > 0.50 mm (L), 0.50-1.00 mm (CL), 0.50-2.00 mm (SL), and 1.00-2.00 mm (SCL) WSA fractions with higher susceptibility by the L > SL > CL > SCL soils. Therefore, cultivation induced macro-aggregate associated SOC and TSN losses are greater in silt- than in clay- and sand- dominated textured soils.

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