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Dynamics of structural indices and organic carbon pool across a haplic acrisol under secondary tropical rainforest at Umudike Abia State

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ABSTRACT

Differences in vegetation types over a landscape influences the structural behaviour and organic carbon pool of soils thereby affecting site-specific management decisions. This study aimed at establishing the differences in structural indices and organic carbon pool across a soil under secondary rainforest vegetation. Nine replicates of auger and core soil samples were randomly collected from the site at 0 – 20 cm depth. Soil samples were prepared and analysed at a laboratory. Data obtained were subjected to geospatial analysis using a Geographical Information System (GIS) software package. Results showed that changes in organic carbon storage ranged from 40 – 48 ton / ha, BD ranged from 1.39 – 1.42 mg / m3, clay flocculation index ranged from 50 – 68 %, aggregated silt + clay ranged from 9 – 12 %, clay dispersion index ranged from 32 – 42 %, dispersion ratio ranged from 26 – 32 %, mean weight diameter ranged from 0.75 – 1.05 mm, saturated hydraulic conductivity ranged from 3.1 – 3.8 cm / mins and total porosity ranged from 46.4 – 47.6 %. Regions of weak micro aggregaion dominated the land while regions of increased stability of macro aggregates were dominant. Regions of increased soil organic carbon storage occupied about half portion of the land. Greater portion of the land was noted for increased bulk density, reduced total porosity and saturated hydraulic conductivity. Consequently, there were changes in soil structural properties and organic carbon storage across the studied area.

Contribution/Originality: There is dearth of information on the spatial variation of structural parameters and organic carbon pool across soils at same vegetation. This study provides such information both in quantitative and qualitative attributes using the arch maps thereby providing information for the various regions of the land for precise soil management.

1. INTRODUCTION

Vegetation is an integral component of soil forming factors; hence, it has the potentials of influencing the physicochemical and biological characteristics of soils by regulating soil climate and impacting on the organic matter content of the soil (Rajendra & Satish, 2023). Consequently, differences in vegetation types, plant density and management of vegetation can have effect on the properties of soils such as bulk density (BD), micro and macro aggregate stability indices, and organic matter content (Nsalambi & Christopher, 2010). Organic carbon content, bulk density and structural stability parameters of soils are among the sensitive soil quality indicators influencing the erodibility of soils and permeability of air, water and plant roots in the soil; therefore, they are relevant in environmental quality and crop productivity assessment (Rivenshield & Bassuk, 2007). Soil organic matter plays significant roles in influencing most physicochemical and biological properties of soil including the buffering capacity of soils and the ability of soil to play its roles in a functioning ecosystem (Islam & Weil, 2000). Soil structural properties such as bulk density and aggregate stability indices are among the key indicators of soil quality and these are greatly influenced by vegetation characteristics and their impact on organic matter content, clay mineralogy, and texture (Bronick & Lal, 2005).

Knowledge of spatial changes of soil properties of vegetated area of a landscape is of paramount important in the efforts to ensuring effective site-specific management and conservation of soils under vegetation cover while alleviating failures in soil quality arising from incorrect generalization (Hironaka, Maynard, & Kenneth, 1990). Variation in vegetation types and plant density is an inherent concept across a landscape and this leads to changes in microclimate which partly influences the nature and property of soils across a landscape (Natural Resources Conservation Service (NRCS), 2007). Meng and Juying (2022) reported that natural vegetation improved soil quality including nutrient status of the soil while artificial vegetation only improved soil nutrient but had no significant improvement on the soil physical characteristics. However, changes in the concentration of vegetation across a land area impacts greatly on the organic matter distribution in the soils of the area, and this can significantly influence the physicochemical properties of the soils including the structural properties (Amanze, Nwosu, Eluagu, Ukabiala, & Amulu, 2023; Oguike, Chika, & Roseta, 2017).

Forest vegetation is associated with increased tree population with limited undergrowth of shrubs, and these give adequate ground cover that moderates the soil temperature and moisture regimes while improving soil organic carbon content by plant residue returns to the soil through litter fall (Meng & Juying, 2022). Dense vegetation cover across a landscape helps to reduce the impact of rainfall drop on the soil thereby forestalling the possibility of increased bulk density and degradation of soil aggregates (Amanze, Oguike, Eneje, Ukabiala, Omatule, Ozomata, & Kolo, 2022); hence, soils with an area of land with poor vegetation cover will be characterized with increased bulk density arising from the impact of rain drop relative to the adjacent soils at the same land but with substantial vegetation cover. The litter falls of the forest plants enhanced the organic matter content of the soil and this positively correlated with the macro aggregate but negatively correlated with the BD (Oguike et al., 2017). There is speculation that variation in plant density in forest vegetation influences the degree of ground cover and organic matter return across the soils thereby impacting changes on organic carbon reserve, bulk density, aggregation and aggregates stability of soils across the vegetated area (Meng & Juying, 2022). Therefore, this study aims at elucidating the concept of spatial changes of structural indices and organic carbon pool of a soil under secondary rainforest vegetation.

2. MATERIALS AND METHODS

2.1. Location And Description of the Study Area

The study was conducted at Umudike, Ikwuano Local Government Area (LGA), Abia State. The area lies within latitude $5^{0}29^{l}$N to $5^{0}31^{l}$N and longitude $7^{0}30^{l}$E to $7^{0}32^{l}$E with mean annual rainfall distribution of 2200 mm (Amanze, Oguike, & Eneje, 2017). Seasons of the year in the area varies from rainy to dry seasons which are commonly experinces within March to October and November to February, respectively. The rainy season peaks in July and September, with short break in August, while the mean annual temperature is about 28^{0}C (Amanze, Oguike, Eneje, Ukabiala, Omatule, Ozomata, Kolo, et al., 2022). The landscape is flat to gently undulating. The parent material is predominantly the Coastal Plain with pockets of alluvial deposits, and the soil was classified as

"Hapludult" according to the United State Department of Agriculture (USDA) soil Taxonomy (Amanze, Oguike, & Lekwa, 2016) and vegetation type is Tropical rainforest.

2.2. Land Use System

The land was a secondary rainforest vegetation (SRV) grown for over 20 years, and it is characterized by indigenous plant species including bread fruit (*Treculia Africana*), bush mango (*Irvingia gabonensis*) oil bean plant (*Pentaclethra macrophyllum) which constituted the tree species while some* shrubs and herbs like "Siam weed" (*Eupatorium odoratum*), sunflower (*Aspillia Africana),* cento (*Centrosema pubesens*) were also present in the land. The soil texture of the area is loamy sand with mean mass of the soil separates by proportion reported as sand = 857.0 g / kg, silt = 69.0 g / kg and clay = 74.0 g / kg (Amanze et al., 2017).

2.3. Soil Sampling and Sample Preparation

Soils were sampled in a simple random sampling method such that nine (9) representative disturbed and undisturbed soil samples were collected from the land at a depth of 0 – 20 cm. The auger (disturbed) soil samples were air – dried and processed before sending to the laboratory for determination of particle size distribution and organic carbon. The undisturbed (core) soil samples were used for the determination of bulk density (BD).

2.4. Laboratory Analysis

Determination of particle size distribution was carried out using the hydrometer method explained in Gee and Or (2002) and reported in Amanze, Oguike, Eneje, Ukabiala, Omatule, Ozomata, and Kolo (2022); the results obtained for silt and clay under water and calgon dispersed soils were used to calculate for micro aggregate stability indices as shown below;

$$\%\ \text{Dispersion ratio} = \frac{\%[\text{Silt} + \text{Clay}(\text{H2O})]}{\%[\text{Silt} + \text{Clay}(\text{calgon})]} \text{x } 100 \qquad (1)$$

$$\%\ \text{Aggregated Silt} + \text{Clay} = \%[\text{Silt} + \text{Clay}(\text{calgon})] - \%[\text{Silt} + \text{Clay}(\text{H2O})] \qquad (2)$$

$$\%\text{Clay flocculation index (CFI)} = \frac{\%\text{Clay}(\text{calgon}) - \%\ \text{Clay}(\text{H2O})}{\%\ \text{Clay}(\text{calgon}} X\ 100 \qquad (3)$$

$$\%\text{Clay dispersion index (CDI} = \frac{\%\ \text{Clay (H2O)}}{\%\text{Clay (calgon)}} X\ 100 \qquad (4)$$

Mean weight diameter (MWD) of Water Stable Aggregates (WSA) was obtained through the wet-sieving method outlined in Kemper and Rosenau (1986) by first analyzing the soils for water stable aggregates of varying size. Then, mean weight diameter (MWD) of the water stable aggregates was calculated as shown below:

$$\text{MWD} = \sum_{i=1}^{n} XiWi \qquad (5)$$

Where Xi is the mean diameter of the ith sieve and Wi is the proportion of the weight of aggregates in the ith sieve.

Bulk density (BD) was obtained through the core method highlighted in Anderson and Ingram (1993) and reported in Amanze, Oguike, Eneje, Ukabiala, Omatule, Ozomata, and Kolo (2022); and then computation was done as shown in the equation below;

$$BD = \frac{\text{Mass of oven dried soil}}{\text{Bulk volume of the soil}} \qquad (6)$$

Bulk volume of the soil is equal to the volume of cylindrical core sampler given as $\pi r^2 h$ where $\pi = 22/7$, r is the inner radius of the base of the cylindrical core sampler and h is its height.

Total porosity (Pt): This was determined by calculation using the bulk density (BD) values assuming a particle density (PD) of 2.65 mg/m^3. The formula is as follows;

$$\% \, Total \, porosity = 1 - \frac{bulk \, density}{particle \, density} X \, 100 \quad (7)$$

Saturated hydraulic conductivity (K_{sat}) was determined by first to determining the rate of water flow through the column of soil using the method outlined in Klute (1986); then, Darcy's equation as provided in Youngs (2001) was applied to calculate the saturated hydraulic conductivity (K_{sat}) as shown below.

$$Ksat = \frac{QL}{AT\Delta H} \quad (8)$$

Where Q is quantity of water discharged (cm^3), L is length of soil column (cm), A is the interior cross – sectional area of the soil column (cm^2), ΔH is head pressure difference causing the flow or hydraulic gradient and T is time of water flow (s).

Soil was analyzed for organic carbon using the dichromate oxidation method explained in Nelson and Sommers (1982) and then the organic carbon pool of the soil was calculated using the formula provided in Amanze, Oguike, Eneje, Ukabiala, Omatule, Ozomata, and Kolo (2022).

$$CT = CF \, x \, q \, x \, D \, x \, 1 \, ha \quad (9)$$

Where C_T is total organic carbon for the layer (metric ton), C_F is the fraction of carbon (percentage carbon divided by 100), q is density of the soil, D is the depth of the soil layer (m)

2.5. Data Analyses

Soil data obtained were analyzed for spatial variability using a GIS analytical software package in line with the geographical coordinates of the sampling points (Amanze et al., 2023).

3. RESULTS AND DISCUSSIONS

3.1. Spatial Changes of Organic Carbon Pool and Bulk Density

The arch maps in Figure 1a and 1b respectively show the spatial changes in organic carbon storage (OCS) and bulk density (BD) of soils of the study area. It revealed that changes in the OCS of the soils ranged from 40 % - 48 % with regions of greatest OCS observed at the extreme southwest and extended through the central region to the northeast as it gradually decreased. Notwithstanding, regions of least OCS were observed at the extreme northwest. Generally, the OCS of the soil was observed to be at the decline within the margin or border areas of the land. Changes in the BD of the soil ranged from 1.39 – 1.42 mg / m^3 with the region of greatest BD observed within the central region and extended northwards and eastwards of the land. The borders of the south and west regions of the land had the least soil BD.

The variation in soil organic carbon pool across the land could be predicted on the variation in plant density and ground cover across the land area such that regions of increased organic carbon pool may have been favoured with increased plant density that possibly translated to high residue return to the soil through litter fall and increased ground cover that intercepted the incoming solar radiation thereby protecting the soil against excessive heat that may increase soil temperature and its consequence on rapid organic matter decomposition and loss (Amanze et al., 2023; Rajendra & Satish, 2023). Conversely, regions within the land with relatively lesser OCS could be regions of less biological activities characterized with low plant density, decreased ground cover which accentuated soil temperature resulting to increased loss of organic matter by oxidation. This assertion agrees with the report of Oguike et al. (2017) that increased exposure of soil to solar radiation raised the temperature of the soil and caused an increased loss of soil organic matter in an arable farmland. It be inferred that regions of increased soil bulk density across the soil may have been prompted by reduced plant density which exposed the soil to direct impact of raindrop and this led to clogging of soil pores by the dispersed soil particles resulting to increased bulk density (Amanze, Oguike, Eneje, Ukabiala, Omatule, Ozomata, & Kolo, 2022; Natural Resources Conservation Service (NRCS), 2007). Also, the observed increase in bulk density around the border area of the studied area may be attributed to the possible movement of humans around such regions which induced increase in soil compaction by overburden effect resulting in increased bulk density (Kutílek & Jendele, 2008). Furthermore, Amanze, Oguike, Eneje, Ukabiala, Omatule, Ozomata, Kolo, et al. (2022) reported a negative relationship between soil organic carbon and bulk density; hence, the possible increase in bulk density at the border area of the land could be predicted on the observed decrease in soil organic carbon in such areas. Consequently, regions of decreased bulk density within the study area may be associated with increased soil organic carbon (Amanze et al., 2017). Regions of the soil with greater organic carbon storage will be expected to have increased microbial activity and the resultant increase in nutrient transformation, low chemical toxicity and improved soil fertility and quality. This inference corroborates the findings of Balesdent, Chenu, and Balabane (2000) that organic matter correlated positively with soil fertility and soil quality parameters and negatively with some heavy metals that were responsible for nutrient toxicity. On the bulk density, it could be inferred that areas on the land with increased bulk density would negatively influence plants root growth and development thereby limiting the plants from accessing sufficient water and nutrients thereby limiting their productivity (Kutílek & Jendele, 2008).

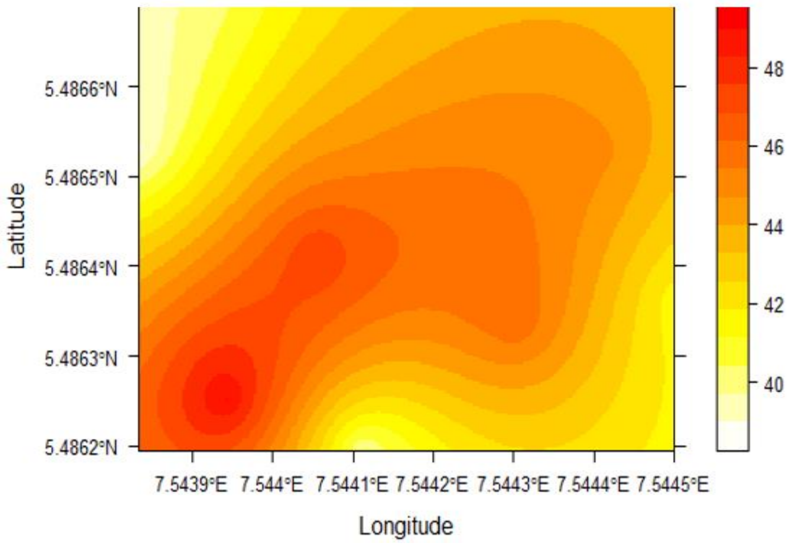

Figure 1a. Spatial changes in Organic carbon storage (ton / ha).

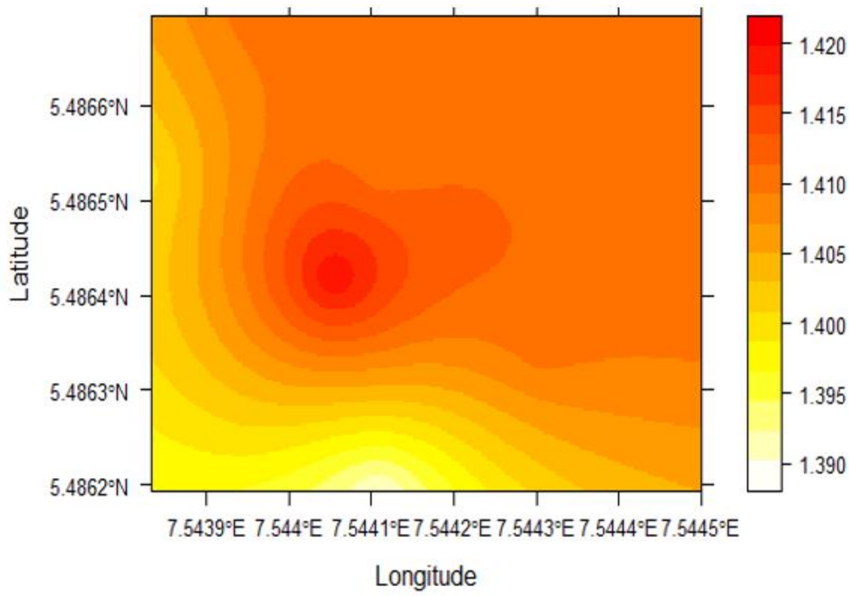

Figure 1b. Spatial changes in bulk density (mg / m3).

3.2. Spatial Changes of Clay Flocculation Index and Aggregated Silt + Clay

There were gradual spatial changes in clay flocculation index (CFI) and aggregated silt + clay (ASC) across the soil of the studied area as shown in arch maps of Figure 2a and 2b, respectively. The CFI ranged from 58 % - 68 %, with regions of least CFI dominating the land area and this spanned from the Northeast through the central part to the extreme Southwest of the land. Meanwhile, there were isolated regions of greatest CFI which were observed at the central part of the extreme south and extreme northwest of the land area. The changes in ASC ranged from 9 % - 12 % with two isolated regions of greatest ASC observed at the extreme northwest and extreme central part of the south. The regions of least ASC extended from the northeast to central region which gradually increased towards the southwest region of the land.

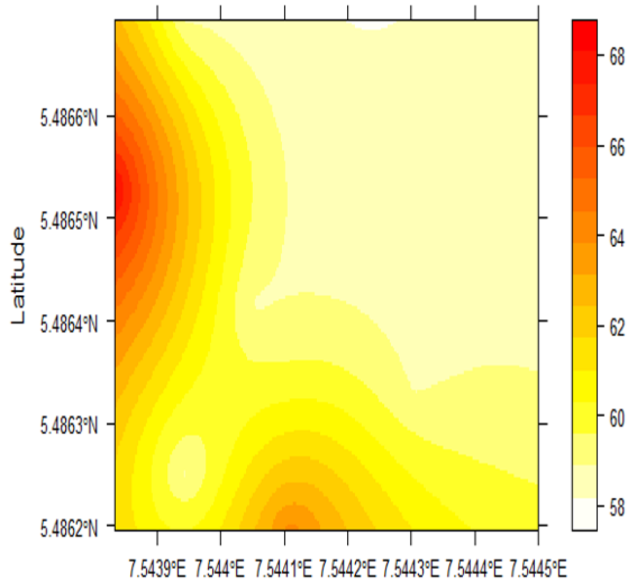

Figure 2a. Spatial changes in clay flocculation index (%).

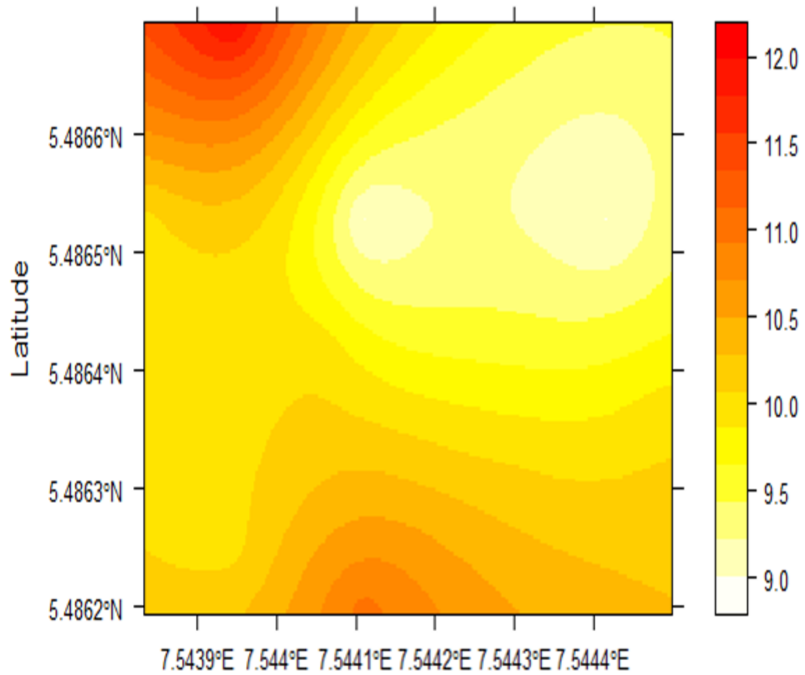

Figure 2b. Spatial changes in aggregated silt and clay (%).

The comparison of the arch maps for organic carbon pool, clay flocculation index and aggregated silt + clay, revealed that regions of increased organic carbon pool had decreased values for stable micro aggregates indicative of reduced clay flocculation index and aggregated silt + clay. The reason for this observation could be associated with dispersing action of organic carbon on clay particles. The report of Nelson and Oades (1998) showed that organic carbon can serve as both binding and dispersing agents to soil particles. Also, Goldberg and Forster (1990) explained that the possible presence of polyanionoc humic substances in organic materials increases the critical flocculation concentration of the soil which is a measure of the minimum concentration of cations required to induce the flocculation of clay particles within the soil colloidal mixture. Consequently, the possible presence of such polyanionic humic substances in the organic carbon pool may have increased the critical flocculation concentration of the soil and weakened the flocculation capacity of the soil leading to reduced clay flocculation index and aggregated silt + clay in such areas. Therefore, regions of the land where there was increased micro aggregation and aggregate stability may be associated with reduced concentration of soil organic carbon that have dispersing effect while regions with decreased micro aggregation and aggregate stability may be concomitant with increased concentration of such soil organic carbon that causes dispersion (Amanze et al., 2023). It could be deduced that the region with reduced flocculation of micro aggregate would be associated with poor soil structure which negatively influence the hydraulic property of the soil as well as its nutrient holding capacity and resistance to erosion, verse versa (Oguike et al., 2017).

3.3. Spatial Changes of Clay Dispersion Index and Dispersion Ration

The Figure 3a and 3b respectively show the arch maps of the spatial changes in clay dispersion index (CDI) and dispersion ratio (DR) across the soils of the study area. Changes in clay dispersion index ranged from 32 % - 42 % with the regions of greatest CDI dominating the area, while regions of least CDI were observed at isolated spots at the extreme westward and central region of the southward. The DR of the soils varied widely with a range of 26 % - 32 %. Regions of least DR were observed at the extreme northeast and southward while regions of greatest DR dominated the northeast to the central region, and then gradually decreased towards the western region of the land.

The changes in clay dispersion index and dispersion ratio across soils of the area were possibly the influence of variation in the organic carbon concentration and differences in the proportion of soil separates across the land. This assertion is in concordance with the report of Meng and Juying (2022) that organic matter plays sensitive role in moderating most physical properties of soils especially those influencing soil structure, and added that variation in the organic matter across soils is greatly responsible for the differences in the soil properties including clay dispersion index and dispersion ratio. Consequently, regions of increased dispersion of micro aggregates could be areas of high critical flocculation concentration (CFC) arising from increased net negative charge possibly contributed by negative polyanionic organic carbon compounds. According to Goldberg and Forster (1990) as reported in Oguike et al. (2017) critical flocculation concentration is the minimum amount of exchangeable cations needed to bind the diffused double layer of clay particles together against dispersion. Consequently, regions of the land with increased dispersion of micro aggregates may be characterized with higher polyanionic organic carbon compounds which increased the CFC of the soils verse versa. Similarly, variation in the clay content of the soil may have contributed to the changes in clay dispersion index and dispersion ratio of the soils across the land. The report of Goldberg and Forster (1990) as recorded in Amanze et al. (2023) revealed that portions of a land with increased clay content were characterized with increased dispersion of clay and micro aggregates arising from increase in the clay flocculation concentration of the soils due to the influence of increased net negative charges at the surfaces of clay particles. It could be deduced that the implication of this observation is that regions of increased dispersion of micro aggregates would be very prone to erosion, loss of recalcitrant organic matter and reduced potentials for carbon sequestration (Malgwi & Abu, 2011).

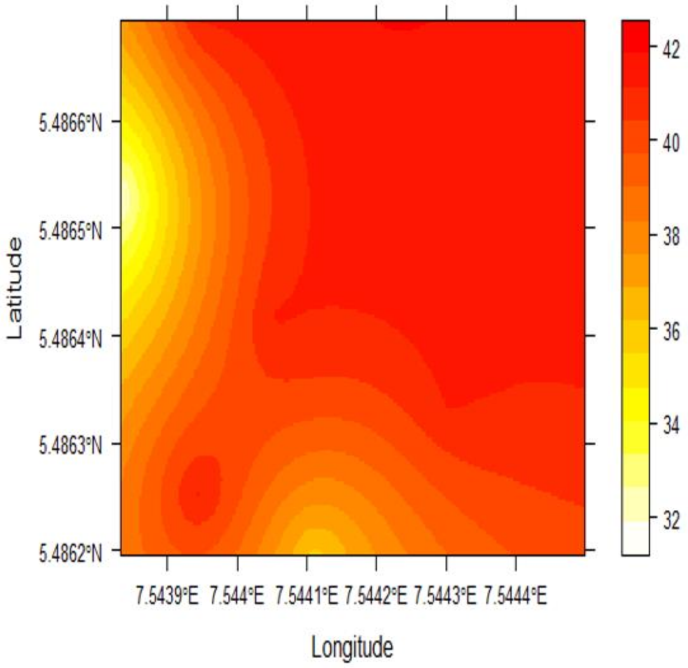

Figure 3a. Spatial changes in clay dispersion index (%).

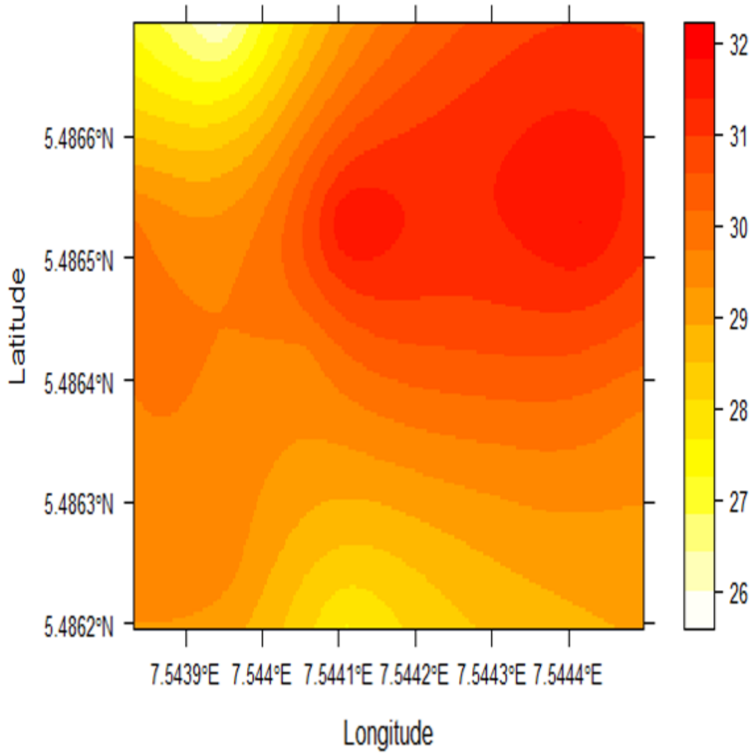

Figure 3b. Spatial changes in dispersion ratio (%).

3.4. Spatial Changes of Mean Weight Diameter

Figure 4 is the arch map showing the spatial changes in mean weight diameter (MWD) of soil of the area. The changes in MWD ranged from 0.75 mm – 1.05 mm with regions of increased MWD observed at the southeast and extreme southwest regions which gradually greatest towards the northeast regions. However, the region with least MWD was observed at the central region of the land towards the west and extended down the central region of the south.

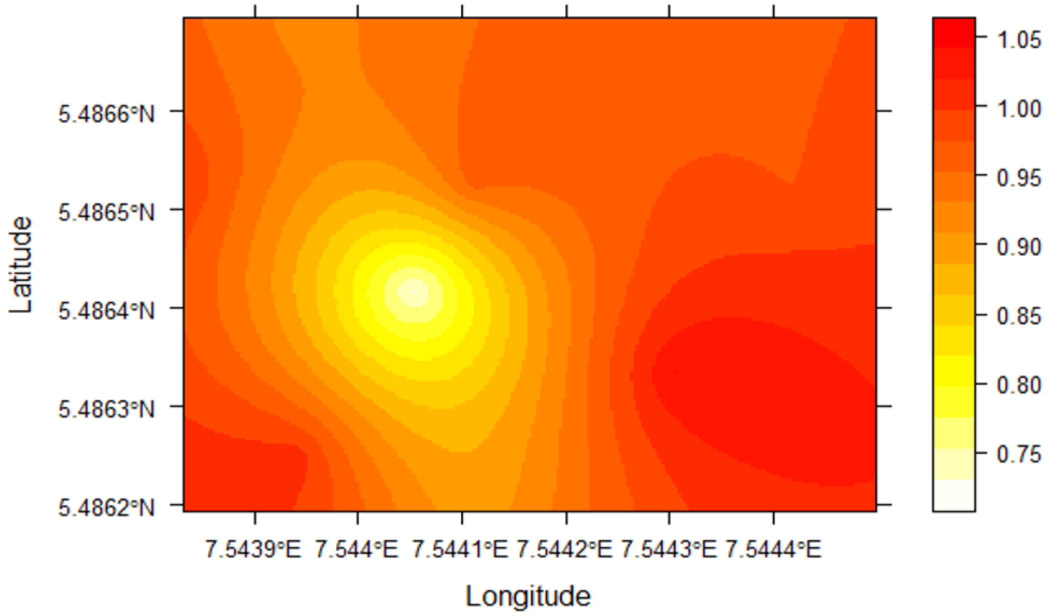

Figure 4. Spatial changes in mean weight diameter (mm).

The variation in mean weight diameter across the soil could be attributed to the possible variation in the degree of vegetation cover across the land area, and this may have influenced the concentration of organic matter deposits across the land and its subsequent implication on macro aggregates. This observation is in agreement with the report of Meng and Juying (2022) that areas of land with increased vegetation cover was characterized with increased macro aggregation which they noted was a result of increased organic matter deposit arising from litter fall and reduced loss of organic matter due to reduced temperature that would have facilitated the decomposition of the organic matter deposits. Consequently, the polysaccharides released during the decay of the deposited organic materials and roots exudates may have aided the aggregation of sand particles and flocculated clay and silt particles into larger aggregates as measured by the mean weight diameter. Also, root hairs and root exudates in areas of increased vegetation may have fostered the enmeshing of soil mineral particles into macro aggregates. This assertion corroborates the report of Oguike et al. (2017) that organic carbon had a significant positive relationship with mean weight diameter. Furthermore, exposure of the soils in areas of low vegetation cover to direct raindrop impact may have resulted in weakening of the macro aggregates resulting to their disaggregation. The report of Amanze, Oguike, Eneje, Ukabiala, Omatule, Ozomata, and Kolo (2022) revealed that areas of land with sparse vegetation had reduced macro aggregates and increased bulk density which was inferred on the increased rainfall impact on the soil which induced the degradation of the macro aggregates.

3.5. Spatial Changes of Total Porosity and Saturated Hydraulic Conductivity

Figure 5a and 5b are arch maps showing the spatial changes of percentage total porosity and saturated hydraulic conductivity, respectively. Figure 5a reveals that there is variation of the volume of pores across soils of the study area. The central part of the southern region extending to the south-western region and the extreme part of the northwest were noted for increased porosity which ranged from 47.0 to 47.6 %. Then, the central region of the land extending to the northwest and due north portions of the land were characterized by reduced porosity which ranged from 46.4 – 46.8 %. Figure 5b shows that there is variation of water transmission capacity of the soils within the study area such that the northern region, part of the central area and the extreme south-western regions of the land had reduced rate of water flow down the profile at saturated condition with saturated hydraulic conductivity (K_{sat}) values ranging from 3.1 – 3.3 cm / mins. Contrariwise, the extreme part of south-eastern region and western part of the central region were noted for increased rate of water transmission down the depth with K_{sat} values ranging from 3.5 – 3.8 cm / mins.

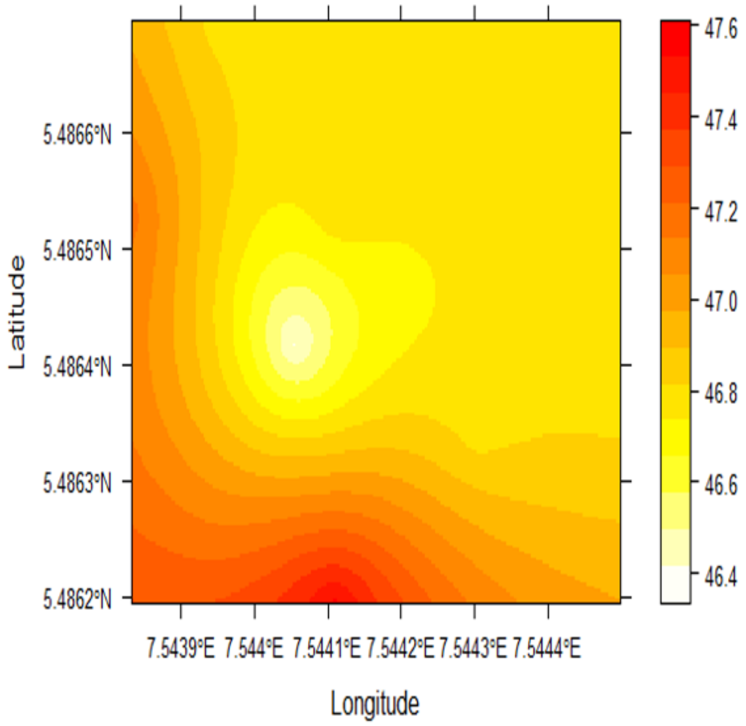

Figure 5a. Spatial changes in total porosity (%).

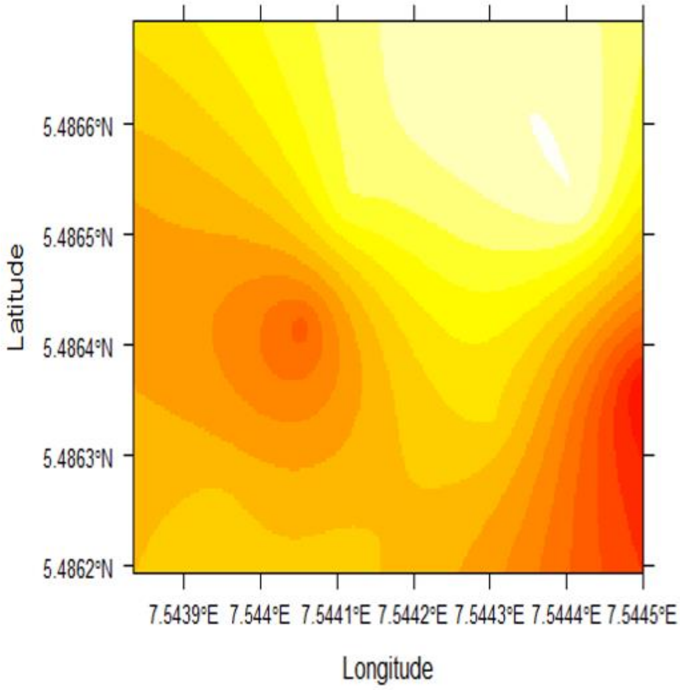

Figure 5b. Spatial changes in hydraulic conductivity (cm / mins).

The variation of the total porosity and saturated hydraulic conductivity across soils of the study area could be attributed to the variation in organic carbon storage and bulk density across the soils. Organic carbon influences the aggregation of soils, and this in turn enhances the formation of macropores which promotes the ease of water flow down the soil depths (hydraulic conductivity) (Amanze et al., 2017). Therefore, regions of the soil with better water transmission may be characterized with better organic carbon storage, vice versa. Conversely, bulk density which is a measure of the degree of soil compaction is known for its negative association with total porosity and hydraulic conductivity of soils (Amanze et al., 2017); hence, regions of the land with increased porosity and hydraulic conductivity may be characterized with low bulk density, vice versa. It could be observed in Figure 5a and

5b that increased porosity does not translate to increased hydraulic conductivity, hence, the size and continuity of pore spaces as may be conditioned by organic carbon in forming aggregates and increasing the size of soil pores could be the major contributing factor responsible for the variation in saturated hydraulic conductivity across the soils, while variation in bulk density which influences the total pore volume of soil per unit area across the land may be responsible for the variation in total porosity (Kutílek & Jendele, 2008). The variation in the water transmission capacity of the soils within the study area implies that the soils vary in erosivity and flooding potentials and also influence irrigation scheduling across the soils such that regions of reduced rate of water transmission may be associated with poor drainage and prone to flooding and erosion as well as accumulation of toxic elements, while regions of increased rate of water transmission may be well drained and aerated. This confirms the report of Ojanuga (2003) and Amanze et al. (2017) that poorly or imperfectly drained soils result from reduced water transmission, increased flooding and erosion.

4. CONCLUSION

There was variation in organic carbon pool, bulk density, aggregate stability indices, total porosity and saturated hydraulic conductivity across the soil under secondary rainforest vegetation in same geographical location and geology. This variation was basically a consequence of variation in the degree of vegetation cover across the land area and this influenced the microclimate of the soils. regions of the soil characterized by weak aggregation should be managed by practicing conservation tillage, then an increased input of organic matter should be encouraged at regions with less organic carbon pool through manuring.

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Authors' Contributions: Developed the concept and design of the research, executed it, funded it, did the writing on the research findings, A.C.T.; proof read, review and revised the write up, N.O.C., E.K.G. and I.O.K. All authors have read and agreed to the published version of the manuscript.

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