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Impact of Road Construction and Agriculture on Soil Aggregate Stability and Aggregate-Soil Organic Carbon: Ultisols of Derived Savannah

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Abstract: The escalating demands of urbanization and population growth in Southeastern Nigeria have subjected the region's soil to increasing pressures from both engineering works and agricultural practices. This study investigates the impact of road construction and agriculture on soil aggregate stability indices (ASI) and aggregate soil organic carbon (ASOC). Two locations, Nsukka and Neke Umo, and five land use types: grazing fallow, forest, road grading, and cultivated areas, were examined in Southeastern Nigeria. Employing the transect method, soil samples were collected at 0-15 cm depth to analyze ASI and ASOC. The findings revealed that tillage and engineering activities negatively impacted aggregation, while grazing and forests promoted soil aggregation. Clay flocculation index (0.4-0.87), aggregated silt plus clay (74-415 g kg^{-1}), water-dispersible clay (36-57 g kg^{-1}), were strongly determined by particle size distribution (PSD), while variations in mean weight diameter (0.7-1.69 mm), linked to land use and PSD was not consistent. Nevertheless,, ASOC was influenced solely by land use, with grazing land and forests displaying higher SOC storage, compared to road grading and cultivated lands. Intriguingly, cultivation was more damaging than road grading in C storage. These findings provide insights for site-specific approaches to enhance soil structure and carbon storage.

Keywords: Road construction, Agriculture, Dispersion indices, Aggregation, Aggregate-SOC

Land serves as a vital resource, offering diverse benefits ranging from food security to social amenities. However, the unbridled exploitation of this limited resource without proper management poses a threat to its sustainability for future use (Verburg et al 2033). In Nigeria, the forces of industrialization and urbanization have led to the creation of new access roads and the re-grading of existing roads without proper asphalt covering (Faiyetole and Adewumi 2024). The escalating population, in turn, exerts pressure on agriculture to meet the demands for food security (Tavershima et al 2022). Civil engineering and agriculture, while utilizing the same material (soil), diverge in their approaches to soil management, may not consider the concept of soil security, which addresses the soil's pivotal role in providing food and other ecosystem services, along with potential threats to sustainability (Evangelista et al 2023). The process of road construction involves the removal of topsoil and compaction, leading to the loss of crucial soil properties such as organic matter, structure, water-holding capacity, and desirable bulk density (Sezgin Hacisalihoğlu et al 2019). Conversely, unsustainable agricultural practices in Nigeria, including continuous cultivation, unrestricted grazing, forest fires, and lumbering, are linked to a decline in soil properties such as percent aggregate stability, mean weight diameter and soil organic carbon storage (Ahukaemere et al 2012, Njoku 2018, Osakwe et al 2021).

Aggregate stability serves as an indicator of organic matter content, biological activity, nutrient cycling, porosity, and soil infiltration. Various indices, such as mean weight diameter, flocculation, and dispersion, have been utilized to predict soil erosion (Nanganoa et al 2019, Nunes 2020). Soil organic carbon enhances nutrient release, improves soil structure, and contributes to the biological and physical health of the soil, promoting climate change mitigation (Thangavel et al 2019, Liu et al 2019).

The detrimental effects of road grading on soil properties, coupled with the unsustainable use of agricultural lands, highlight the need for a comprehensive assessment of the impact on aggregate stability and soil carbon storage. Understanding these changes is crucial in the context of climate change scenarios, with implications for infrastructural services, food security, and climate change mitigation. This study addresses this gap by evaluating the effects of agricultural land use and road construction on soil aggregate stability and aggregate-associated soil organic carbon in Nsukka and Neke-Uno, Southeastern Nigeria.

MATERIAL AND METHOD

This investigation was carried out in Nsukka (NS) and Neke Uno (NU) located in Enugu State, within the derived savannah of southeastern Nigeria. Positioned between N06°.37.901' and N06°.51.138' latitude and E007°.32.024' and E0070.25.520' longitude, the region experiences a tropical wet season from April to October and a dry season from November to March, with an average annual precipitation of 1600 - 1800 mm and an average temperature of 28°C.

Enugu State's soils, originating from sedimentary deposits, fall under the Ultisol order (Soil Survey Staff 2010). Nsukka's soils, part of the Nsukka formation (Ezeaku et al 2015), are classified as Typic Paleustult(Ukaegbu and Akamigbo 2021). The soil is characterized by deep red to brownish-red soil (Igwe 2001, Nwite and Obi 2008) as a result of $Fe_2O_3$and Al_2O_3 known as sesquixides which consists the major cementing agent (Igwe and Akamigbo1999). Two soil series:Nkpolugu and Nsukka series were identified within Nsukka study location (Ukaebu and Akamigbo 2021). Neke Uno on the other hand, rests on the Campano-Maestrichtian sediment of South-Eastern Nigeria, known as the Enugu Shale, featuring dark grey, fissile shale with occasional thin beds of Siderite and Mudstone (Okamkpa et al 2018) (Table 1).

The study was laid as 2 * 5 factorial experiment, denoting two locations (Nsukka (NS) and Neke Uno (NU)) and five land use types (Grazing, Forest, Road Grading, Fallow, and Cultivated), was replicated thrice in a randomized complete block design. The **respective Geo-positions and elevations at each location across the land use types were read with GPS (Table 1).** Transect sampling method was employed to collect soil samples at 0-15cm depth, replicated three times for each of the five land use types in both locations.

Air-dried composite samples were sieved into > 2 mm and < 2 mm fractions for analysis. The former was utilized for water-stable aggregates, macro-aggregate stability indices, and carbon associated with water-stable aggregates, while the latter was used for particle size distribution, micro-aggregate stability indices, and soil organic carbon in bulk soil. Physical analysis involved hydrometer-based particle size distribution determination (Kalra and Maynard 1991). Micro-aggregate stability indices, including Water dispersible clay, Aggregated Silt + Clay (ASC), Clay ratio and Clay Flocculation Index (CFI), were calculated from silt and clay measurements in calgon and water as follows:

ASC = [Total clay (g/kg) + Total silt (g/kg)] – [WDC (g/kg) + WDS (g/kg)]

CFI I = Total clay (g/kg) - WDC (g/kg)/ Total clay (g/kg)

CR= [Sand (g/kg) + silt (g/kg)/ clay (g/kg)

The distribution of water stable aggregates was estimated by the wet sieving technique (Kemper and Rosenau 1986). To separate the water stable aggregate, 25 gm samples of the > 2 mm air dried aggregates was put on top of a nest of two sieves measuring 0.25 mm, 0.053 mm and was pre-soaked for 10mins in water. The sieves and their content were oscillated vertically, once per second, in water 20 times using 4cm amplitude. The resistant aggregates on each sieve were oven dried at 60 ºC for 24 hr and weighed. The mass of < 53 micron WSA was obtained by difference between the initial sample weight and the sum of sample weight collected on the >2 mm, 0.25 mm and 53 micron sieve nest.Mean weight diameter (MWD) was calculated:

$$MWD = \sum_{i=1}^{n} Wi\,Xi$$

Where Wi is weight of aggregate in the ith aggregate size range as fraction of dry weight of sample and Xi is mean diameter of any particular size range of aggregates separated by sieving. Soil organic carbon in whole soil and

Table 1. Description of study locations and land use history

Loc	Tex	LU	Latitude	Longitude	Elev(m)	LU history
NS	SL	GRZ	N060.51.163'	E0070.25.520'	476.7	UNN Pasture land
	SL	GRD	N060.51.138'	E0070.25.698'	472.4	UNN Road Project
	LS	FAL	N060.51.609'	E0070.26.107'	472.8	NF 12 years
	LS	FST	N060.51.393'	E0070.26.337'	476.4	Secondary Forest
	LS	CLT	N060.51.417'	E0070.26.280'	477.6	Arable >15years
NU	SL	GRZ	N060.38.360'	E0070.32.078'	206	Cattle Free Range
	SL	GRD	N060.37.901'	E0070.32.024'	193.2	Road project
	L	FAL	N060.38.374'	E0070.32.078'	204.2	NF >15years
	CL	FDT	N060.39.908'	E0070.31.850'	208.4	Secondary forest:
	SL	CLT	N060.38.404'	E0070.31.802'	204.2	Arable, >15 years

Elev.- Elevation, Loc.- Location, LU-Land use, GRZ-Grazing, RGD,, Road Grading, FAL, Fallow, Forest, FRS, CLT, Cultivated, NF, Natural fallow,NS- Nsukka, NU- Neke Umo, UNN- University of Nigeria, Nsukka, SL- Sandy loam, LS- Loamy sand, L- loam, CL- Clay loam water-stable aggregates was assessed using the Walkey and Black wet oxidation method as modified by Nelson and Sommer (1996).

Statistical analysis: Data analysis was performed using Minitab statistical software. Tukey tests at 5% probability level was used to separate significant differences in the means of the variables examined. Simple linear correlation analysis was conducted using SPSS to establish relationships between aggregate stability indices, aggregate soil organic carbon and soil properties. These methodologies aimed to explore the impact of agricultural land use and road construction on soil aggregate stability and associated organic carbon in Nsukka and Neke Uno, Southeastern Nigeria.

RESULTS AND DISCUSSION

Influence of land use on soil particle sizes and micro aggregate stability indices: CLT(691 g/kg) andRGD (684 g/kg)showed significantly higher sand content compared to other land use types, attributed to topsoil disturbance during tillage and the removal of topsoil during road construction respectively (Table 2). The forest (FRS) and fallow (FAL) land use exhibited the highest clay content. This is consistent with the result of Osakwe et al (2013). The observed increase in sand content is indicative of soil degradation and a decline in soil fertility.

Variations in particle sizes between study locations were significant, attributed to differences in parent materials. The interaction of location and land use on PSD was highly significant, giving rise to different textures within and between locations (Table 1). The differences in soil series within NS location affected PSD hence FRS from Nsukka series depicted lower clay content compared to GRZ and RGD in Nkpologu series in the same location. Kolo et al (2022) reported that variations in texture in a land use study was not linked to land use which underscores the complexity of response of soils to land use. This also highlights the need for soil management practices tailored to the specific characteristics of different soil environments. CLT land use exhibited the highest water-dispersible clay (WDC) and the lowest aggregated silt plus clay (ASC) (Table 2), suggesting that tillage destroyed aggregation and enhanced clay release (Li et al 2023).

The location effect indicated 55 and 20 % higher ASC, CFI and 90 % lower CR in NU respectively compared to NS. The comparison provided insight into differences that may exist in the susceptibility of soils to erosion in different soil environments. However, higher yield of WDC in NU

Table 2. Influence of land use on soil particle sizes and micro aggregate stability indices in study locations

Parameter		Sand	Clay	Silt	WDC	ASC	CR	CFI
L U	GRZ	656bc	146bc	195a	47b	197bc	5.88a	0.68a
	RGD	684a	143bc	172a	46b	175bc	6.17a	0.68a
+	FAL	639c	171ab	187a	43b	227b	6.99a	0.68a
	FRS	614c	200a	188a	45b	250a	6.62a	0.63a
	CLT	691a	126c	177a	54a	169c	7.34a	0.54b
LOC.								
	NU	515b	204a	282a	50a	280a	0.72a	4.58b
	NS	803a	111b	84b	44b	127b	0.57b	8.67a
LU LOC								
NS	GRZ	742C	139cd	119b	36.0c	180bc	0.74abc	6.18bc
	RGD	764bc	147cd	89bc	40.8bc	162bcd	0.71abcd	5.86C
	FAL	841a	84e	75bc	36.0c	108dc	0.56de	11a
	FRS	862A	84e	54c	50ab	74d	0.40f	11.08a
	CLT	820ab	99de	81bc	57.6a	109cd	0.41ef	9.11ab
NU	GRZ	569d	152c	272a	57.6a	214b	0.62cd	5.6cd
	RGD	635d	140cd	256a	50.4ab	187bc	0.63cd	6.5bc
	FAL	435e	258b	300a	50.4ab	346a	0.80ab	2.86de
	FRS	368e	310a	315a	40.8bc	426a	0.87a	2.15e
	CLT	569d	272a	152c	50.4ab	228b	0.67bcd	5.58cd

NU- Neke Uno, NS- Nsukka, LU- Land use, LOC-Location GRZ-Grazing, RGD- Road Grading, FAL- Fallow, Forest- FRS, CLT- Cultivated, WDC, -Water dispersible clay, ASC-Aggregated Silt + Clay, CFI,- Clay Flocculation Index, CR-Clay ratio compared to NS , infers that WDC may be a function of total clay which aligned with the report of Osakwe et al (2014). The interaction of land use and location was highly significant, with FR and FAL in NU consistently showing higher CFI, ASC, and lower CR across all land use types. This underscores the role of intrinsic soil properties in controlling micro aggregate stability (Osakwe et al 2021a). Enhanced aggregation is crucial for soil pore connectivity, aeration, root penetration, and water infiltration. The decline in ASC may lead to soil dispersion, erosion, siltation, sedimentation, and pollution of water bodies (Igwe and Udegbuna 2008).

Influence of land use on aggregate size distribution (ASD) and mean weight diameter (MWD): The effect of land use on ASD revealed that GRZ land exhibited the highest percentage of WSA in the 4-2 mm fraction, with the order of GRZ > FAL > FRS = RGD > CLT. In the 2-0.25 mm fraction, GRZ, FAL, and FRS had similar percentages, while RGD and CLT showed lower values (Table 3). This suggests that tillage and engineering activities led to the destruction of macro aggregates (> 0.25 mm), while grazing, fallow, and forests promoted soil aggregation. Micro aggregates (0.25-0.053 mm) increased in RGD, indicating potential macro aggregate loss during road construction. Furthermore, the MWD was highest in GRZ compared to all land uses while RGD and CLT depicted the lowest MWD (Table 3). The higher the MWD, the more resistant the soil is to erosion. The implication is that RGD, and CLT will increase soil erodibility and consequently reduce the soils ability to sustain ecosystem functions..NU, consistently showing higher WSA in all aggregate sizes and MWD compared to NS, suggesting NU's higher resistance to external forces. The higher yield of WSA at micro aggregate level in NU may be attributed to more colloidal materials compared to NS (Table 2). The interaction of land use and location on ASD demonstrated that GRZ in NS had the highest 4-2 mm WSA, attributed to effective pasture management. FRS and RGD in NS exhibited the lowest WSA due to the coarse nature of FRS soil (Table 1) and topsoil removal during construction respectively. For the 2-0.25 mm fraction, GRZ in NU had the highest value, similar to other land use types, except for CLT and RGD in NS and NU, respectively, which showed the lowest aggregation. The results indicated that tillage and engineering activities negatively impacted soil aggregation, influenced by both land use and soil characteristics.

The lowest WSA in the 0.25-0.053 mm fraction occurred in GRZ of NS, suggesting higher stability hence lower yield at the lower aggregate sizes, while RGD in NU exhibited the

Table 3. Influence of land use on aggregate size distribution (ASD) and mean weight diameter (MWD) in study locations

AGS (mm)		4-2	2-0.25	0.25-0.053	<0.053	MWD
Parameter			% WSA			mm
L U	GRZ	41.55a	28.98a	8.347c	10.30ab	1.59a
	RGD	23.16c	21.00b	25.28a	12.46a	0.96d
+	FAL	26.74b	30.69a	13.80b	11.27ab	1.23b
	FRS	25.65bc	27.70a	14.05b	9.49ab	1.04c
	CLT	17.12d	23.60b	16.62b	6.85b	0.89d
LOC.						
	NU	29.29a	27.6a	21.61a	9.70a	1.20a
	NS	24.52b	25.19b	9.53b	9.37b	1.003b
LO*LU						
NS	GRZ	46.48a	25.40ab	3.65e	Wr4	1.69a
	RGD	15.30ef	26.96ab	11.49cd	17.77a	0.78e
	FAL	33.87cd	29.27ab	11.49cd	5.79b	1.36c
	FRS	12.40f	26.29ab	11.55cd	7.07b	0.68ef
	CLT	14.56cd	18.02c	9.95d	4.62b	0.65f
NU	GRZ	36.83bc	32.55a	13.0cd	9.01b	1.49b
	RGD	31.00d	15.04c	39.07a	7.14b	1.14d
	FAL	19.60e	32.13ab	16.11cd	16.76a	1.10d
	FRS	38.92b	29.11ab	16.55c	9.91b	1.41bc
	CLT	19.69e	29.18ab	23.30b	9.09b	1.13d

See table 1 and 2 for details

highest value, indicating lower aggregate resistance. For <0.053 mm aggregate size, RGD and FAL in NS and NU had the highest values, implying reduced stability due to road construction and unprotected fallow. The MWD results reflected macro aggregation, with GRZ in NS having the highest value and CLT and FRS in the same location recorded the lowest value. The result suggests that land use and PSD influenced macro-aggregation, however their inconsistencies prevented a conclusion, indicating additional factors' involvement. The findings are consistent with Njoku's 2018 report, showing lower mean weight diameter (MWD) in crop land compared to other land uses. However, our study reveals higher MWD in Grazing land than Forest, contrary to Njoku's findings. This difference may be attributed to effective pasture management and inherent soil properties in present study sites.

Influence of land use on aggregate soil organic carbon (ASOC) and soil organic carbon in bulk soil: Significant effects of land use on soil organic carbon (SOC) were observed in aggregates and bulk soil (Table 4). FRS and GRZ consistently had the highest SOC across aggregate sizes and bulk soil, except for 4-2 mm WSA in GRZ. Lowest SOC accumulation occurred in FAL, CLT, and RGD. Remarkably CLT depleted SOC in the largest aggregates (4-2 mm WSA) emphasizing the impact of tillage on SOC associated with large aggregates. The effect of location on ASOC was significant at the macro-aggregate level, with NS exhibiting higher SOC in 4-2 and 2-0.25 WSA compared to NU. However, no significant difference was observed at the microaggregate level, indicating a decline in location effects with decreasing aggregate size. Bulk soil SOC was 4% higher in NU than NS, emphasizing the variability in SOC storage between locations and aggregates. Understanding both storage potentials is crucial for monitoring ecosystem carbon budgets in different soil environments.

The interaction of land use and location on aggregate-associated soil organic carbon highlighted NS's highest SOC storage potential in GRZ and FRS, except for 4-2 mm WSA in GRZ. Continuous cultivation in NS depleted SOC in large aggregates, emphasizing the importance of external organic carbon inputs. RGD at NS showed the lowest capacity to store carbon at 2-0.25 mm and 0.25-0.053 mm sizes, aligning with findings on road construction impacts reported by Nosareti et al (2016). The interaction of land use on SOCb values reflected highest values in GRZ at NS and FRS at NU, supporting the positive influence of grazing and forest land

Table 4. Influence of land use on aggregate soil organic carbon (ASOC) and soil organic carbon in bulk soil in study locations

AGS (mm)		4-2	2-0.25	0.25-0.053	
Parameter			ASOC (g/kg)		SOCb (g/kg)
L U	GRZ	18.42b	25.1a	15.80b	14.13a
	RGD	8.2c	8.39b	8.04d	8.55b
+	FAL	8.9c	7.69b	9.1d	8.71b
	FRS	24.15a	26.52a	20.81a	13.40a
	CLT	3.91d	9.40b	12.98c	8.91b
LOC.					
	NU	10.41b	13.65b	13.11a	10.96a
	NS	14.72a	17.21a	13.50a	10.52b
LO*LU					
NS	GRZ	13.81cd	18.88b	12.08cde	11.00b
	RGD	4.99g	12.89c	14.32cd	7.18ef
	FAL	10.19ef	6.89de	10.70def	11.04b
	FRS	17.00c	21.93b	19.08ab	17.29a
	CLT	7.83fg	7.66de	9,36ef	8.11de
NU	GRZ	23.05bc	31.40a	19.5a	17.19a
	RGD	11.52de	3.86e	1.77g	9.14bc
	FAL	7.78fg	8.5cde	7.5f	6.38f
	FRS	31.3a	31.11a	22.54a	9.51cd
	CLT	0.00h	11.15cd	5.30ef	9.71bC

See table 1 and 2 for details

Table 5. Correlation of aggregate stability indices, aggregate soil organic carbon with with particle size distribution and SOC in bulk soil (SOCb)

Location	Parameter	Sand	Silt	CLAY	SOCb
NU	WDC	0.74ns	0.64s	0.77ns	0.63n
	CFI	-0.97**	0.95**	0.98**	0.81ns
	CR	0.99**	0.9**	-0.98**	0.85ns
	ASC	-0.91**	0.97*	0.98**	0.88*
	MWD	-0.19ns	0.21ns	0.18ns	0.62ns
	ASOC1	-0.7ns	0.74n	0.68ns	0.93*
	ASOC2	0.29ns	0.23n	0.3ns	0.69n
	ASOC3	-0.55ns	0.41ns	0.59ns	0.72ns
NS					
	WDC	0.46ns	0.5ns	-0.39	-0.23
	CFI	-0.99***	0.81ns	0.85	0.54
	CR	0.97**	0.82ns	0.99***	-0.68
	ASC	0.99**	0.94***	0.93***	0.69ns
	MWD	-0.47ns	0.69ns	0.26ns	0.51ns
	ASOC1	0.03ns	-0.1ns	0.02n	0.41n
	ASOC2	0.01ns	0.09ns	0.09ns	0.62ns
	ASOC3	0.25ns	-0.09ns	-.35ns	0.44ns

WDC-Water dispersible clay, ASC-Aggregated Silt + Clay, CFI,- Clay flocculation Index, CR- Clay ratio,MWD-Mean weight diameter, ASOC1, SOC in 4-2 mm WSA, ASOC2, SOC in 2- 0.25 mm WSA, ASOC3, SOC in 0.25-0.053 mm WSA

use on SOC. Road construction in NU recorded the lowest SOC storage, confirming that land use practices are crucial for SOC enhancement.

Correlation of aggregate stability indices, aggregate soil organic with particle size distribution and SOC in bulk soil: Correlation analysis revealed strong relationships between soil particle sizes and microaggregate stability indices (r = 0.99 - 0.86) at both locations indicating that particle size distribution controls microaggregate stability (Table 5). However, MWD, ASOC, and ASD were not related to particle size and SOC except significant positive relationship of SOCb with ASOC in large WSA (4- 2 mm), suggesting the involvement of other factors in aggregation and carbon dynamics. Osakwe et al (2014) in a land use study in south eastern Nigeria related variations in aggregate properties to total clay, diothionate citrate bicarbonate iron oxide and SOC.

CONCLUSION

The study investigated the impact of road construction and agriculture on soil aggregate stability and associated soil organic carbon in southeastern Nigeria. The result demonstrated that road construction and tillage negatively impacted soil aggregation and soil organic carbon both in aggregates and in bulk soil with implications for soil erosion susceptibility, while grazing and forests promoted soil stability and carbon storage. The result also suggested that micro aggregate stability was strongly influenced by particle size distribution an inherent property of the soil other than land use. This underscores the importance of discouraging blanket management strategies and optimize management practices that target the peculiarity of different soil environment. While land use and particle size distribution exerted control over macro-aggregation their inconsistencies prevented a conclusive determination, indicating the involvement of additional factors in the observed variations. However, the research highlighted the significance of land use in influencing aggregate-associated soil organic carbon, with implications for carbon storage, ecosystem carbon budgets and climate change mitigation. Overall, the findings demonstrated the need for sustainable land management practices to mitigate the adverse effects of road construction and tillage on soil structure and C storage in southeastern Nigeria.

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