

RESEARCH PAPER

Spatial Distribution of Soil Organic Carbon Stocks, and Soil Total Nitrogen in Central Equatorial State, South Sudan

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ABSTRACT

The composition of soil organic carbon (SOC) and soil organic nitrogen (SON) is imperative to soil health in different agroecological zones globally. The proliferation of anthropogenic activities triggers the nitrogen and carbon stocks in soils. This study presents the spatial distribution of SOC and SON in six counties in Central Equatoria State, South Sudan counties. This study sought to determine the effect of pastoral activities on SOC and SON. We collected the soil samples within a 12-14 km radius from specific areas including congregation, grazing, degraded, water points, and agricultural land. The soil was collected at depths of 0–10 cm, 10–20 cm, and 20–30 cm respectively. The results indicate that land use activities had varied impacts on SOC and SON at different depths. The results showed that the interactive effects of the three sites and land uses differed in soil organic carbon (SOC) under different soil depths, which varied from 0.3 to 5.3%. The grazing area also recorded a higher SOC than the other land use types under 0-10 cm soil depth. The means showed that the SOC in the deep soils (20-30 cm) was lower than the surface soils in all the areas and land uses. The interactive effects of the districts and land uses differed in soil organic carbon (SOC) under different soil depths, which varied from 0.3 to 5.3%. The highest mean SOC of 5.73% was recorded in 0-10 depth in Kajokeji in the grazing area. The grazing area also recorded a higher SOC than the other land use types under 0-10 cm soil depth. The means showed that the SOC in the deep soils 20-30 cm was lower than the surface soils in all the areas and land uses. The results thus underscore that study areas and land use activity could impact the SOC and SON directly or indirectly.

HIGHLIGHTS

- ① Soil organic content and soil organic nitrogen concentrations decreased with the increase of soil depth in most land uses, implying that management of topsoil is paramount.
- ② The grazing area exhibited higher soil organic carbon and soil organic nitrogen concentrations than other areas, which may be related to manure and urine deposits and trades-off the losses from plant tissues.
- ③ Land use types have far-reaching changes in soil organic carbon and nitrogen as shown by variation in different districts.

Keywords: Soil Organic Carbon, Soil Organic Nitrogen, Carbon Stocks, Nitrogen, Grazing Intensity

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Over the past century, the global average temperature has been projected to increase by approximately 0.7°C (Cassandro, 2020; Gaikwad *et al.* 2022; Bojajo *et al.* 2024; Shu *et al.* 2024). According to the Intergovernmental Panel on Climate Change (IPCC), this rise is largely attributed to human activities emitting greenhouse gases like carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and halocarbons (Bassous *et al.* 2024; Easterling *et al.* 2023; Jones *et al.* 2023; Ngare *et al.* 2020). Agriculture, particularly the livestock sector, is not only a significant contributor to these emissions but also one of the sectors most vulnerable to the impacts of climate change.

Soils are the most extensive terrestrial reservoir of carbon (C), with approximately 1500 Pg of organic C within the upper meter globally (Bojajo *et al.* 2022; Rabach *et al.* 2020). Consequently, minor alterations in the soil organic carbon (SOC) reservoir can substantially affect atmospheric carbon dioxide (CO₂) concentrations. With increasing atmospheric CO₂ levels, there has been a heightened pursuit of SOC sequestration over the past decade (Li *et al.* 2022). Grasslands are projected to sequester 10–30% of the global soil organic carbon (SOC), with a carbon sequestration rate of 0.5 Pg of carbon per year (Batjes, 2018). Grassland soils possess significant potential for carbon sequestration, functioning as a sink for atmospheric CO₂ and aiding in climate change abatement (Adeola *et al.* 2023; Ngare *et al.* 2022).

Grazing intensity can affect Soil Organic Carbon (SOC) of the amount and the type of organic matter that gets into the soil (Louault *et al.* 2005). Studies (Murray, 2023; Benton *et al.* 2021) conducted in animal pastures have shown that gorging increases vigorous root dynamics and soil microbiology and has many environmental and biogeochemical consequences. Mechanisms, which may include grazing, changes in the availability of resources, and species breakdown through mechanical wear, can affect plant community structure (Randal *et al.* 2019). Global livestock manure emissions contribute 14.5% of anthropogenic emissions, mainly from beef and dairy production (Gerber *et al.* 2013). Cumulatively, Africa contributes about 2.73% of greenhouse gasses to the Global Emission Index. In Sub-Saharan Africa, GHG emissions from livestock are mainly associated with a large cattle population in Eastern Africa,

including South Sudan. South Sudan reported CO₂ emissions index was about 1.33 (MtCO₂e) in 2012, contributing to 0.00036% of the global GHG cumulative index (USAID, 2012).

Soil serves as a critical reserve of important nutrients for earthly organisms, significantly contributing to water conservation efforts, organism activity, and biodiversity (Zhang *et al.* 2024). Maintaining soil fertility is essential for enhancing ecosystem stability and mitigating climate change. Furthermore, examining various kinds of soil carbon (C) and nitrogen (N) is essential for improving our comprehension of the metabolism of nutrients in terrestrial ecosystems, which is vital for preserving soil quality and ecosystem health (Ntinyari and Gweyi-Onyango 2021). Approximately 62% of South Sudan's total land area is covered by grass (Land Cover Atlas South Sudan, 2011). Grasslands account for the largest share of the country's grazing land and pastures, making them important in ruminant livestock's diet. This study therefore sought to determine the effect of pastoral activities on (SOC) and Soil Total Nitrogen (STN).

METHODOLOGY

Study area

The study was conducted in the Central Equatorial State, South Sudan. Geographically, the State lies on the longitudes 29° 47' 32" and 32° 10' 22" and latitudes 3° 29' 15" and 6° 14' 52" respectively. In land mass, the area covers approximately 43,131 km² (Fig. 1). The study was localized in six counties, namely, Terekeka, Lanya, Juba, Morobo, Kajo-Keji, and Yei.

Sampling Soil Organic Carbon Stocks and Soil Organic Nitrogen

At depths of 0–2.5 cm, 2.5–5 cm, 5–10 cm, 10–20 cm, and 20–30 cm, the soil was collected using manual auger in five replicates from each of the agro-ecological zones. Excavations were done purposely to estimate bulk densities in every soil layer - giving different soil masses in each agroecological zone (Segnini *et al.* 2019). The penetrometer collected samples from each depth interval and pooled them for subsequent soil dry evaluation weight. Samples of all communal grazing systems were made within a 12–14 km radius in specific congregation areas,

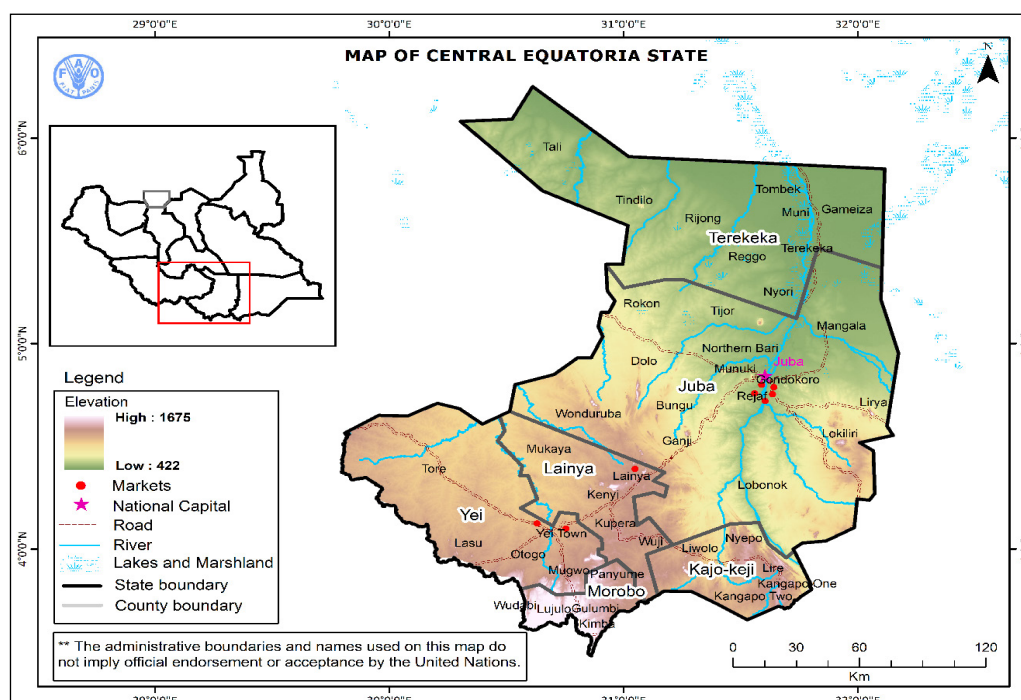


Fig. 1: Map indicating the study area

grazing areas, destroyer zones, water points, and orphaned areas.

Total carbon stocks were estimated using soil bulk density (BD) corresponding to carbon content at specific depth intervals (Equation 1).

$$\text{Carbon stock} = \text{Soil carbon content} \times \text{BD} \times \text{Layer depth} \times 10 \quad \dots(1)$$

Where;

Carbon stock (Mg ha^{-1}); BD = bulk density (Mg m^{-3}) and sampled soil layer depth/ thickness in (cm). Soil carbon stocks by soil layer were determined through depth readings (0–2.5 cm, 2.5–5 cm, 5–10 cm, 10–20 cm, and 20–30 cm). The totals were compared across all agroecological zones (Veldkamp, 1994).

To estimate Organic nitrogen measurement concentration in the agro-ecosystem target livestock grazing intensities, the following computation was performed (Parries *et al.* 1987; Sainju, 2017) aided by the Equation 2:

$$\text{STN} = \text{STNc} \times \text{BD} \times T \times 10000 \quad \dots(2)$$

Where;

STN = soil total N content (kg N ha^{-1}); STNc = soil

total (N) concentration (g N kg^{-1}); BD = bulk density (Mg m^{-3}), T = thickness of the soil layer (cm), and 10,000 = conversion factor.

Analysis was done at the experimental onset and closure to compute the total nitrogen content of the soil for collected samples (Meisinger and Randall, 1991; Bremner, 1996). Thus, the soil mass method was used to fine-tune the mass of soil throughout calculations of BD and the total nitrogen content per soil layer to affect management practice and time. Therefore, the entire soil profile (N) content values were added to the soil total of N content from the individual layers under experimentation.

Sampling tools

The sampling tools included a penetrometer machine for onsite soil sample excavation, sampling bags for collection of excavated soil and collected vegetation, and markers for labeling sample bags. Then after, the samples were transported to the lab for analysis.

Sampling transects

Soil and vegetation sample transects were randomized at all communal grazing systems in the Central Equatoria State within the five livelihood

zones. It was customized to a 12-14 km circle radius in each specific congregation area, grazing area, destroyer zone, water point, and orphaned area (Fig. 2).

The transect survey was adopted to detect the grazing intensity along elevation and soil gradients. A preliminary desk study was performed to create randomly distributed transects over each livelihood zone using geospatial analyst tools (Google Earth Engine, SEPAL) overlaid with optical satellite images. Fig. 2 below shows the study's soil sampling points according to the Soil Taxonomy classification system, which was developed by the United States Department of Agriculture (USDA) in Central Equatorial State (CES).

Laboratory analysis

The air-dried soil samples were pounded and sieved through 2 mm to remove any debris and then subjected to physical and chemical analysis following standard methods described by Okalebo *et al.* (2002). Soil pH was measured using a pH meter in a soil water solution ratio of 1:2.5; electro-conductivity by use of a meter; Organic carbon by potassium dichromate wet acid oxidation method; nitrate nitrogen by calorimetric method; bulk density by gravimetric method; and particle

size distribution (texture) using the Bouyoucos (hydrometer) method.

RESULTS AND DISCUSSION

Spatial distribution of soil organic carbon and soil organic nitrogen

Soil Organic Carbon

The interactive effects of the three sites and land uses differed in soil organic carbon (SOC) under different soil depths, which varied from 0.3 to 5.3% (Table 1). The highest mean SOC of 5.73% was recorded in 0-10 depth in Kajokeji under the grazing area. The grazing area also had a higher recorded of SOC than the other land use types under 0-10 cm soil depth. The means showed that the SOC in the deep soils (20-30 cm) was lower than the surface soils in all the areas and land uses.

The distribution of soil organic carbon (SOC) with depth varied among areas and land uses. The SOC concentrations of different areas and land uses decreased with increasing soil depth, with SOC concentrations in the surface layer (0–10 cm) of areas being higher than those in the middle layer (10–20 cm) and bottom layer (20–30 cm). Zhao *et al.* (2023) stated that when the SOC concentration of the

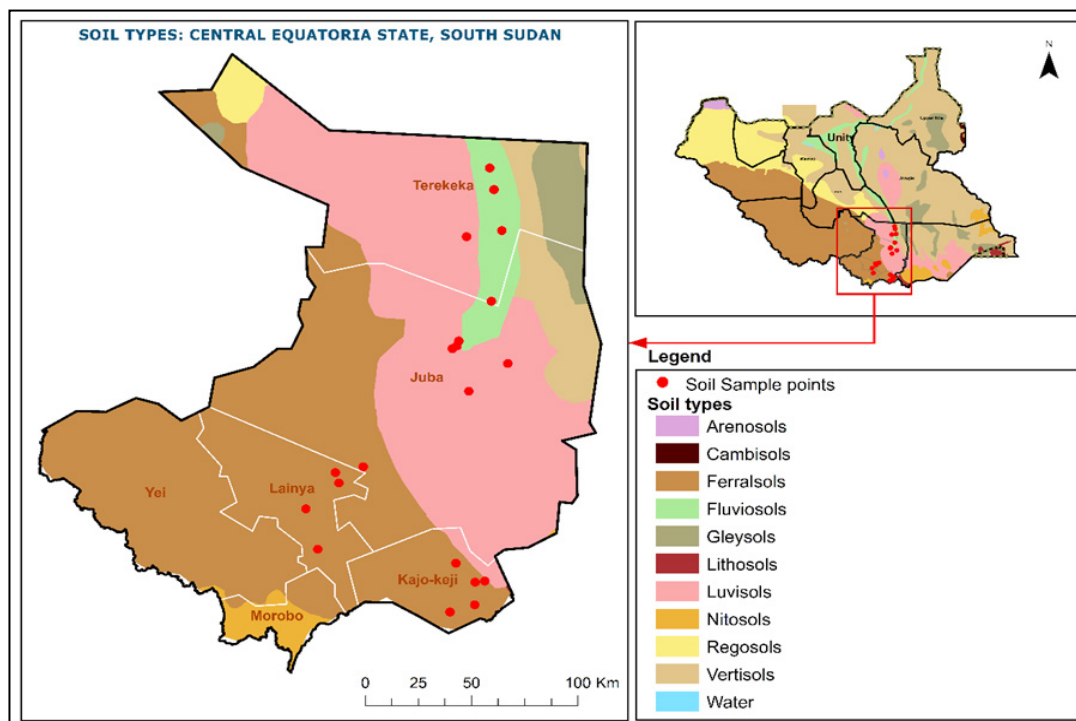


Fig. 2: The map showing soil sampling points



surface layer is much higher than that of the middle and bottom layers, it is called surface aggregation. This could be due to the developed plant roots in the surface soil and the easy accumulation of vegetation litter promoting the growth of microorganisms, which in return these organisms accelerate the decomposition of vegetation litter to form humus (Zhao *et al.* 2021; Nyawade *et al.* 2019), thereby increasing the concentration of SOC on the soil surface. Additionally, the soil surface can directly engage in external material and energy exchange, promoting the accumulation of SOC.

Table 1: Mean soil organic carbon for interactive effects between districts and land uses under different soil depths in Central Equatorial

		Organic carbon (%)		
		Soil depth		
District	Land uses	0-10 cm	10-20 cm	20-30 cm
Kajokeji	Agriculture	3.31 ^{bcd}	1.47 ^d	1.47 ^d
	Congregation	3.21 ^{bcd}	2.32 ^c	1.72 ^{cd}
	Grazing	5.73 ^a	3.57 ^b	2.94 ^b
	Degraded	2.84 ^{bcd}	1.37 ^d	0.47 ^e
	Water point	5.30 ^a	4.44 ^a	3.85 ^a
Terekeka	Agriculture	1.63 ^{ef}	3.54 ^b	2.76 ^b
	Congregation	2.65 ^{bcdde}	3.61 ^b	2.32 ^{bc}
	Grazing	3.63 ^b	2.32 ^c	1.77 ^{cd}
	Degraded	2.30 ^{de}	3.79 ^{ab}	2.54 ^b
	Water point	0.72 ⁱ	0.54 ^e	0.30 ^e
Juba	Agriculture	2.76 ^{bcdde}	1.77 ^{cd}	1.57 ^d
	Congregation	3.50 ^{bc}	1.53 ^{cd}	1.48 ^d
	Grazing	3.31 ^{bcd}	2.33 ^c	1.43 ^d
	Degraded	2.44 ^{cde}	1.69 ^{cd}	1.72 ^{cd}
	Water point	3.46 ^{bc}	1.65 ^{cd}	1.36 ^d
P value		<0.001	<0.001	<0.001

The means with similar letters within the column are not significantly different at $p < 0.001$.

Grazing showed higher SOC in Kajokeji and Terekeka, especially in 0-10 cm depth. This response could be tied to the long-term exposure to moderate grazing increased SOC mineral concentrations, particularly within the top 15 cm of mineral soil (Hewins *et al.* 2018; Malo *et al.* 2024).

Soil Organic Nitrogen

To determine the effect of different districts and land uses on soil organic (SON), a statistical study was conducted in the central equatorial (CES).

Table 2 shows the mean organic nitrogen differed significantly among the soil depths as influenced by the interactive effect of districts and land uses. The highest organic nitrogen of 0.47% was recorded in the Kajokeji district, along the grazing area in 0-10 cm depth. This was followed closely in the same district and in the water point area which gave a total of 0.46% organic nitrogen. Generally, the SON concentrations decreased with soil depth in most of the land uses.

Table 2: Mean soil organic nitrogen for interactive effects between districts and land uses under different soil depths in Central Equatorial

		Organic nitrogen (%)			
		Soil depth			
District	Land uses	0-10	10-20 cm	20-30 cm	0-30 cm
Kajokeji	Agriculture	0.28 ^b	0.13 ^c	0.12 ^c	0.18 ^{de}
	Congregation	0.28 ^b	0.15 ^c	0.13 ^c	0.19 ^{cde}
	Grazing	0.47 ^a	0.34 ^a	0.26 ^b	0.36 ^a
	Degraded	0.26 ^b	0.06 ^d	0.04 ^d	0.12 ^f
	Water point	0.46 ^a	0.37 ^a	0.36 ^a	0.39 ^a
Terekeka	Agriculture	0.15 ^c	0.25 ^b	0.24 ^b	0.23 ^{cd}
	Congregation	0.15 ^c	0.25 ^b	0.14 ^c	0.18 ^{de}
	Grazing	0.25 ^b	0.24 ^b	0.14 ^c	0.21 ^{cd}
	Degraded	0.23 ^{bc}	0.34 ^a	0.24 ^b	0.27 ^b
	Water point	0.06 ^d	0.04 ^d	0.04 ^d	0.05 ^g
Juba	Agriculture	0.25 ^b	0.16 ^c	0.15 ^c	0.18 ^{cde}
	Congregation	0.25 ^b	0.15 ^c	0.13 ^c	0.80 ^{cde}
	Grazing	0.24 ^b	0.26 ^b	0.15 ^c	0.22 ^c
	Degraded	0.28 ^b	0.07 ^d	0.15 ^c	0.17 ^e
	Water point	0.24 ^b	0.16 ^c	0.16 ^c	0.29 ^{cde}
P value		<0.001	<0.001	<0.001	<0.001

The means with similar letters within the column are not significantly difference at <0.001 .

The results in Table 2 indicate that the interactive effect of geographical location and land use activities had varied impacts on soil organic nitrogen. There were high records of organic nitrogen in grazing areas both in Kajokeji and Terekeka. This is because grazing also converts a major portion of vegetation nitrogen (N) to urea which is returned to the soil in urine form. According to Gelaw *et al.* (2014), soil carbon and nitrogen stock are affected by land use due to the different input quantities of organic matter. Livestock grazing modifies the carbon (C) and N cycle which may change C

and N accumulation in soil (Pinheiro *et al.* 2006). Therefore, it is crucial to comprehend the dynamics of soil nitrogen stocks in various agroecosystems due to topographic position, land use, and their interaction to develop sustainable land management alternatives (Fig. 3) that contribute to food security. According to Abebe *et al.* (2020), the dynamics of soil total nitrogen alter in response to climatic and environmental shifts, and biotic and abiotic factors both have an impact.

According to Abebe *et al.* (2020), the dynamics of soil total nitrogen alter in response to climatic and environmental shifts, and biotic and abiotic factors both have an impact. In addition, the rate of N cycling through the soil-plant-animal system increases with grazing intensity because N excreted by livestock is in a more mineralized form than vegetative N (Baron *et al.* 2002; Gweyi-Onyango and Ntinyari 2022). Although, grazing can elicit diverse impacts on SON within the soil, contingent upon the intensity of grazing and its associated management practices. Moderate and light grazing can augment the soil's nitrogen stock by introducing organic

matter and nutrients via the deposition of manure, urine, and litter. Conversely, elevated grazing intensity can potentially diminish the soil's nitrogen stock by promoting the degradation of soil organic matter and facilitating leaching.

Temporal and spatial variations in depth and land use type

The analytical results in Table 3 show how the depth's effect (0-10, 10-20, and 20-30 centimeters, respectively) on organic carbon and organic nitrogen. From the analytical processes, at a depth of 0-10c m, organic carbon (3.38%) and organic nitrogen (0.22%) at a: $p \leq 0.001$ show significant variations. The observed column mean average depth thus was found to be significantly different.

The land use types that demystified grazing intensities were categorized as Water points (WP), Congregation areas (CA), Grazing area (GA), Degradation area (DA) and Agricultural land (AI). To ascertain the probable significance of carbon and nitrogen, the mean at a significance $p < 0.001$

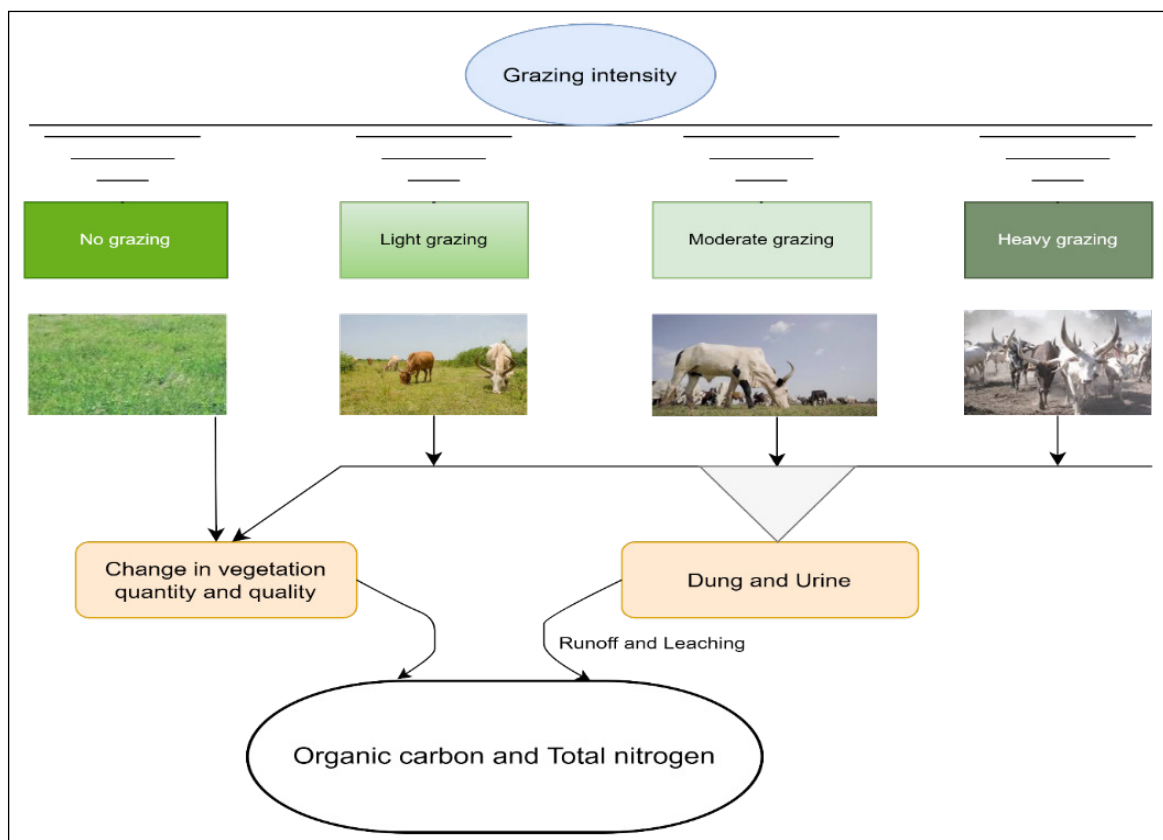


Fig. 3: Systematic diagrammatic showing the conceptual flow of dynamics that inform the carbon and nitrogen contents in different ecosystems in the study site



was computed. From ANOVA, the means followed by the same letter within the same column are not significantly different ($p < 0.001$) refer (Table 4). The findings show significant variation of soil organic carbon and nitrogen across all land use types at depth of 20-30cm. At the same depth, the agricultural land with 1.84%, with highest variation of soil organic carbon, and water points with 1.07% had the least. However, this was different in organic nitrogen at the same depth.

Table 3: Effect of soil sampling depth on organic carbon and organic nitrogen

Depth	Organic carbon (%)	Organic nitrogen (%)
20-30	1.46 ^c	0.09 ^c
10-20cm	2.16 ^b	0.14 ^b
0-10cm	3.38 ^a	0.22 ^a
<i>p</i> -value	0.001	0.001
Land use type	Organic carbon (%)	Organic nitrogen (%)
Water point	1.95 ^a	0.13 ^a
Congregation area	2.18 ^a	0.15 ^a
Grazing area	2.50 ^a	0.16 ^a
Degraded area	2.50 ^a	0.16 ^a
Agriculture land	2.54 ^a	0.16 ^a
<i>p</i> value	0.001	0.501

Means followed by the same letter within the same column are not significantly different ($P < 0.001$).

Further, results in Table 4 shows no significance in the congregation areas and water points for both soil organic carbon and organic nitrogen. The agricultural land, degraded area, and grazing areas were found to be significant, $p < 0.001$. Therefore, only agricultural land, grazing areas, and degraded land were significant among the five determinant land use types, with soil organic carbon and organic nitrogen.

The results in Table 3 show a minimal nitrogen concentration index at the watering points among other land use types. This was prompted by the abundance of free-flowing water promoting the dilution and dispersal of nitrogenous waste products from livestock, such as urea in urine (Siddiqi and Jabeen, 2022). The limited duration of livestock at the watering points resulted in a decrease in excreta deposition, compared to areas

where animals spend more time (Reimer *et al.* 2024; Spiess *et al.* 2024; Egeru *et al.* 2015). Furthermore, the continuous movement of animals around the watering point is causing soil disturbance, inhibiting the prolonged accumulation of manure and urine.

Soil organic carbon (SOC) and soil total nitrogen (STN) are important attributes of soil quality and fertility, and they are influenced by various factors such as climate (Hewin *et al.* 2018), vegetation, soil type, and management practices (Zhou *et al.* 2020). Grazing, as a common land use practice, can affect SOC and STN by altering plant productivity, litter input, root biomass, soil microbial activity, and nutrient cycling (Liu *et al.* 2023; Farzadfar *et al.* 2021).

Table 4: Effect of soil sampling depth on organic carbon and organic nitrogen

Land use type	Depth	Organic carbon (%)	Organic nitrogen (%)
Agriculture land	20-30cm	1.84 ^{bc}	0.011 ^{def}
	10-20cm	2.30 ^{abc}	0.15 ^{abcdef}
	0-10cm	3.47 ^a	0.22 ^{abc}
Congregation area	20-30cm	1.20 ^c	0.09 ^{ef}
	10-20cm	1.85 ^{bc}	0.12 ^{cdef}
	0-10cm	3.47 ^a	0.24 ^a
Degraded area	20-30cm	1.59 ^{bc}	0.11 ^{def}
	10-20cm	2.41 ^{abc}	0.16 ^{abcdef}
	0-10cm	3.51 ^a	0.20 ^{abcd}
Grazing area	20-30cm	1.61 ^{bc}	0.10 ^{def}
	10-20cm	2.37 ^{abc}	0.15 ^{abcdef}
	0-10cm	3.53 ^a	0.23 ^{ab}
Water point	20-30cm	1.07 ^c	0.07 ^f
	10-20cm	1.88 ^{bc}	0.13 ^{bcdef}
	0-10cm	2.90 ^{ab}	0.19 ^{abcde}
P value		0.001	0.001*

Means followed by the same letter within the same column are not significantly different ($p < 0.001$).

According to different researchers (Liu *et al.* 2023 and Farzadfar *et al.* 2021; Malo *et al.* 2024), grazing can have positive, negative, or neutral effects on SOC and STN depending on the grazing intensity, duration, frequency, and type of livestock. Moderate grazing can stimulate plant growth and root turnover, increase litter decomposition and soil microbial biomass, and enhance SOC and STN sequestration (Li *et al.* 2022). However, overgrazing

can reduce plant cover and diversity, expose soil to erosion and compaction, decrease soil water retention and nutrient availability, and degrade SOC and STN stocks.

The effects of grazing on SOC and STN may also vary across different types of lands (Olorunfemi et al. 2020; Bandak et al. 2024). Grazing areas that have native grasses or legumes may have higher SOC and STN than agricultural lands that have been cultivated or fertilized (Yang et al. 2019; Piñeiro et al. 2010). Degraded lands with low plant productivity or high soil disturbance may have lower SOC and STN than grazing areas or agricultural lands with better management practices.

CONCLUSION

We conclude that soil composition significantly varied with different agroecological zones in different counties depicting variations of SOC and STN stock indexes as influenced by different anthropogenic activities. Moreover, the SOC and STN stock indexes varied across different land use cluster types, watering points, agriculture, congregation areas, degraded areas, and grazing areas. In determining the STN index, the county with the highest nitrogen stock impacted by the cattle grazing factor was Kajokeji, with 33.90 kg/ha and 30.22 kg/ha, and Lanya had the lowest mean index, 13.10 kg/ha and 9.16 kg/ha. Moreover, it was observed that different land use activities have varied impacts on STN; therefore, the congregation areas factor and grazing intensity don't mainly determine the Soil Total Nitrogen (STN).

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