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Land-Use Change on Soil C and N Stocks in the Humid Savannah Agro-Ecological Zone of Ghana

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Abstract

Land-use conversion and unsustainable farming practices are degrading native forest ecosystems of Ghana's humid savannah agro-ecological zone. This study assessed the impact of land-use change on soil C and N stocks in different land-use systems and soil types. A total of eighty (80) composite soil samples at two depths (0 - 20 cm and 20 - 50 cm) were sampled from five land use types (Forest, Woodland savannah, Grassland, Fallow and Cropland) for laboratory analyses. Particle size distribution, bulk density, pH, SOC and TN were determined using standard procedures. Results of the study indicated that C and N stocks were significantly lower in croplands ($p < 0.05$) compared to other land-use systems. There were significant interactions ($p < 0.05$) within land-use systems, soil types, and soil depth for soil C and N stocks. Acrisol and associated soils had the highest C and N stocks. A strong positive significant correlation ($p < 0.05$) was observed between C and N stocks with an R^2 value of 0.85 and 0.93 for the 0 - 20 and 20 - 50 cm depth, respectively. Soil C and N stocks in the study area were estimated to be 34.56 kg/m^2 and 4.63 kg/m^2 for soil types and 26.89 kg/m^2 and 3.39 kg/m^2 for land use types, respectively for the 0 to 50 cm soil depth. Our findings indicated that the conversion of native forest to arable land has significantly reduced soil C and N stocks in the top 50 cm (0.50 m) soil layer by 50.77% and 47.77%, respectively. Therefore, we conclude that land-use change, soil type, and soil depth influenced soil C and N stocks of land-use systems in the humid savannah agro-ecological zone of Ghana.

Keywords

Land Conversion, Nutrient Dynamics, Soil C and N Stocks, Soil Type, Land-Use

1. Introduction

Agricultural systems are under pressure worldwide due to increasing population pressure, which has resulted in soil resource degradation [1]. Globally, land-use change due to the conversion of forest to arable land increases atmospheric CO_2 emissions and influences natural occurrences and ecological processes [2] [3] [4]. Soil carbon performs a significant function in the carbon cycle of different ecosystems. Clearing forests and their conversion into arable land decreases soil water holding capacity, biological activity, nutrient supply, and storage in soil [5] [6]. This has reduced the potential level of most arable lands in the tropics and subtropics. Soil organic matter is influenced by a balance between input (mostly from plant growth), and output (decomposition and transport) is determined by diverse factors relating to natural and/or anthropogenic sources [7] [8]. Soil carbon and nitrogen are determinants for monitoring soil quality [9] and agricultural sustainability [10] in agroecosystems. The global carbon pool in the top metre (1 m) as stored in terrestrial ecosystems is estimated to be 477 Gt C. Tropical Forest soils contain about 216 Gt C, savannah soils had been estimated at 264 Gt C, and croplands had 128 Gt C in soils [11]. Also, grasslands had high SOC stocks (343 Gt C) stored in the 1-metre depth due to the presence of a high C allocation below ground, root turnover, as well as the release of organic C compounds by roots (rhizodeposition) [12]. Also, about 128 Gt C is stored in the soils of cropland because croplands release up to 30% of SOC stocks in the 1-metre soil depth in tropical regions [13].

In West African agroecosystems, including Ghana, the equilibrium between input and output is in danger due to the availability of few inputs to compensate for the harvested biomass as a significant output [14]. Recovery of natural vegetation (fallow) seems to be a unique way to restore soil fertility. Additionally, primary production is low in this biome due to low or erratic rainfall, inherent soil fertility, and inadequate farm management practices [11]. For instance, soils with low clay content limit the potential capacity to store SOM in savannah biomes, and this has resulted in low carbon saturation levels [15]. Lal *et al.* [16] and Dawidson and Nilsson [17] observed that carbon input, climate, soil texture, pH, and drainage characteristics affect soil carbon pool and CO_2 fluctuations in land-use systems. The depletion of SOC is primarily due to erosion, runoff, and leaching [14] [18]. Erosion and runoff have a high impact on SOC in smallholder cultivated farmlands compared to natural forest and savannah biomes [19]. Bationo and Buerkert [20] and Bombelli and Valentini [21] demonstrated that rapidly depleting SOC level is associated with continuous cropping. Several research findings stress that unsustainable farming practices (e.g. continuous cultivation without using fertiliser, crop residue burning or removal, overgrazing, etc.) are common, and these decrease SOC by diminishing inputs to the soil [22]

[23] [24] [25]. According to Nandwa [26], land clearance and continuous cultivation increase mineralisation and reduce SOC up to 30% in smallholder farms. However, intercropping systems and the use of cover crops increases soil nutrient stocks [14] [20].

Similarly, Roose and Barthes [18] observed that carbon depletion through soil erosion could be 4 - 20 times higher in natural vegetation. Also, lone use of mineral fertilizers depletes SOC by decreasing base saturation, increasing nutrient leaching, and soil acidification, thereby reducing soil quality. Cropping and agricultural management practices such as minimum tillage can reduce erosion rates and increase SOC balance [27]. Lepsch *et al.* [28] and Van Leeuwen *et al.* [29] stressed that the conversion of natural forests into arable land has a negative impact on soil ecosystem function, and these changes lower soil fertility. An increase in anthropogenic perturbation on native forests alters soil physical, chemical, and biological processes [4] [30]. Also, ecosystems depend on C and N fluxes mediated by microbial interactions in the soil-plant and animal food web [31] [32]. The key factors controlling and stabilising soil C and N stocks include land use, soil properties, geographical area, climate variability, and the dominant vegetation composition on a soil landscape.

Soil micro-organisms contribute about 1% - 3% carbon to the total soil carbon [33] and are highly susceptible to land-use change due to changes in litter composition and root turnover rates [34] [35] [36]. Croplands experience tremendous soil degradation, which reduces soil organic matter by allowing decomposers access to previously unavailable carbon compounds [2] [37] [38]. Hence, C and N storage decrease and barely recover under intensive cropping. Several studies on carbon-nitrogen dynamics [39] [40] [41] concluded that soil carbon and nitrogen stocks vary across land-use systems, soil types, and soil depth due to substrate quality and quantity, edaphic factors and biodiversity of most tropical soils [42] [43]. A study by Solomon *et al.* [44] revealed a decrease in SOC and nitrogen after converting native forests to maize fields in the humid tropics of South-Eastern Ethiopia, with SOC stocks ranging from 58.3 to 63.9 Mg C ha^{-1} on cultivated fields. In similar research, Lemenih and Itanna [45] observed a significantly low soil C and N stocks in natural vegetation following subsequent conversion to agricultural production systems in South-Central Ethiopia.

Although few studies have been conducted in the study area on soil property variability under natural vegetation and croplands, a few have addressed the effect and impact of native forest conversion into arable systems [46] [47]. Most studies [16] [48] emphasized that tropical soils possess unique features and capabilities to store carbon and a high percentage of clay and silt increases soil carbon stocks compared to sandy soils. Also, existing knowledge on the interactions between soil type and land use is rare. The study area is characterized by a great diversity of soil types [24] [49] [50] due to its location between the Guinea Savannah in the north and the Forest zone in the south of Ghana. The transition from forest to savannah and verse versa has created forest-savannah-derived vegetation with numerous soil types influenced by climate (temperature and rainfall) and vegetation. Also, deforestation in the forest-transition zone is caused mostly by smallholder farmers because fallow periods used to restore soil fertility have reduced in recent decades [51]. The need to increase the productivity of arable lands has resulted in the degradation of these farms [52], and an increase in yield results from an expansion inland than crop improvement.

During policy formulation processes, there is the need to close the knowledge gap between the impact of climate change and extractive farming systems that leads to soil and/or land degradation at the local, regional and global levels [53]. These policies should stress why improving soil conservation and making this information accessible to farmers is essential to national policies. For example, the "4 per 1000 Initiative" is a global soil initiative launched in 2015 by France [54] [55]. This policy initiative stresses that policy measures should include sustainable agricultural approaches such as agroforestry, conservation agriculture, and landscape management processes that build up soil organic matter. We hypothesized that land-use change decreases C and N stocks in soil type and soil depth. This study: 1) Examines the effect of land use on soil C and N stocks; 2) Assesses the interactive effect of land use, soil type, and soil depth on C and N stocks in the Nkoranza District of the Transitional agro-ecological zone of Ghana.

2. Materials and Methods

2.1. Site Description

The study was carried out in Nkoranza (North and South) District in the Bono East Region (**Figure 1**). Nkoranza District is bounded by latitude 7˚20'N & 7˚55'N and longitude 1˚10'W & 1˚55'W and covers an area of 2592.09 km^2 [56] [57].

Nkoranza District is located in the transitional ecological zone between the Guinea Savannah to the north, which has only one rainy season, and the Forest Vegetation to the south with two rainy seasons. According to the Koppen-Geiger Climate Classification, the study area experiences the equatorial climatic regime, exhibiting the tropical wet savannah climate (Aw) [58]. Rainfall ranges between 1200 mm and 1700 mm, with an annual average of 1350 mm. The rainfall pattern is bimodal. The beginning and the end of the rainy season, as well as the overall monthly and annual rainfall amounts, vary greatly [59] [60]. The wet season, which corresponds to the growing season, is defined as the period from April to October, with 80% of the annual rainfall, while the dry season is defined as the period from November to March determine the activities of smallholder farmers [24] [61] [62] in the study area. Temperature is high with a maximum of 33˚C and a minimum of 20˚C [63]. The average monthly temperature varies from 30˚C in March to 24˚C in August, with average yearly temperatures ranging between 26.5˚C and 27.2˚C [64]. Actual and annual evapotranspiration is about 1200 mm and 1400 mm, respectively [65]. Relative humidity ranges from

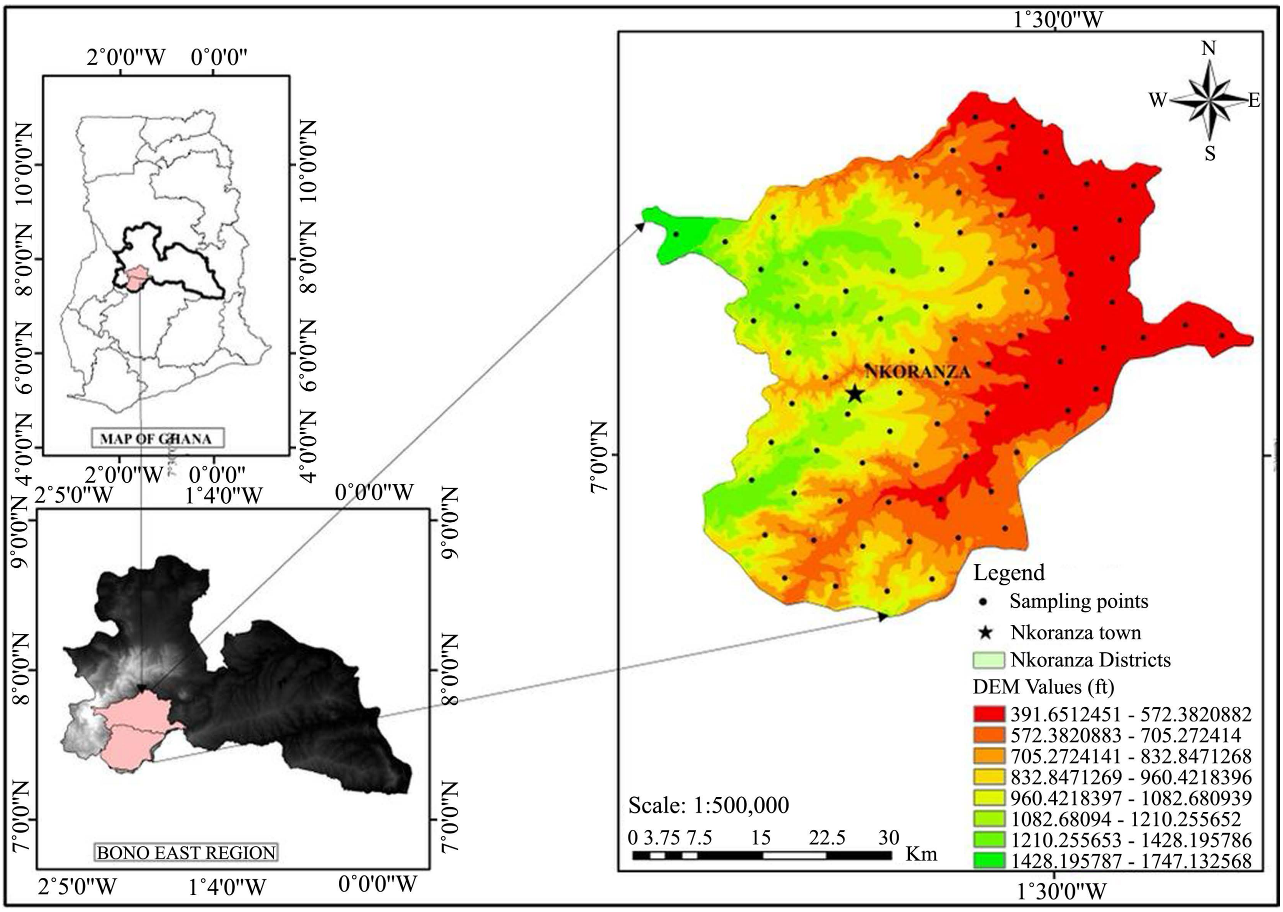

Figure 1. Geographical location of Nkoranza (north and south) district with soil sampling points.

90% to 95% and 75% to 80% in the rainy and dry seasons. Also, average monthly values may be around 80% at mid-day during the rainy months of June to September and are lowest during the Harmattan months, with readings of approximately 70% in the morning and 40% at mid-day [64].

2.2. Soil Sampling and Description

A soil sampling depth of 0 - 20 and 20 - 50 cm depth were adopted because it represents the average plough layer and the depth to which plant nutrient and clay particles are leached in an area with high rainfall. A total of eighty (80) soil samples (0 - 20 cm and 20 - 50 cm) were sampled. These soil samples were collected from five (5) land-use systems (**Table 1**).

The Land Degradation Surveillance Framework (LDSF) sampling method was adapted to fit the farm structure of smallholder farmers (ranges from 1 - 10 acres) [66] [67]. Placing the actual sampling locations (**Figure 2**) on the dots at the specified distances of 2.88 (25 m^2), 3.99 (50 m^2), and 5.64 (100 m^2) meters from the centre of the plot, a composite sample for each location was obtained [67] [68]. An auger was used at each location to sample soils up to 20 cm (topsoil) and 20 - 50 cm (subsoil) depths. The reason for using this sampling pattern was to obtain composite samples representing a 100 m^2 area, as illustrated in

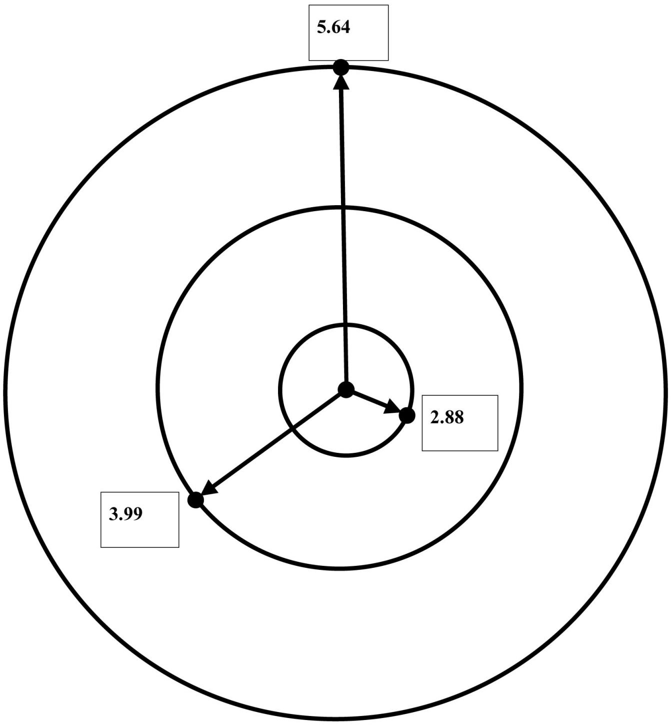

Figure 2. Illustrates soil sampling layout. The distance along the radial arm between the plot centre-point to the centre of the up-slope sub-plot centre is 12.2 m. The 3rd and 4th sub-plots were offset at 120 and 240 degrees from the centre-point downslope. The black dots indicate soil sampling sub-plots with a radius of 2.88 m (area = 25 m^2), 3.99 m (50 m^2) and 5.64 m (area = 100 m^2). The entire plot has a radius of 17.84 m (area = 1000 m^2).

Table 1. Land-use types were identified in the study area.

Land-use type	Number of Sampling Sites	Mean depth of soil samples (cm)
Forest (Fo)	6	221
Woodland savannah (SWL)	12	179
Grassland (GL)	14	98
Fallow (Fa)	22	155
Cropland (CL)	26	181

Figure 2. Two soil samples were taken from each selected point: 1) A composite sample collected from four points within the plot at 0 - 20 cm depth following the layout in **Figure 2** (topsoil); 2) A composite sample from the four plot points at 20 - 50 cm depth (subsoil). For each site, land-use type was identified. At each examination point, soil cores (5 cm diameter) were sampled. To characterise soil types according to the Ghana interim classification system [49], soil depth, texture, colour, coarse fragment, etc., were some soil properties considered. These soils were reclassified based on the FAO-WRB classification system [69]. Information on vegetation, climate, and land-use types was also recorded on the field.

Interpretation of soil data required some standards for comparison. Based on these, soils sampled from arable lands were compared with naturally forested soils where the natural cycle and ecosystem were fundamentally different. Global Positioning System (GPS) coordinates were also taken at each observation point. Soil samples taken to the lab were air-dried and sieved through a 2 mm mesh to remove stones, roots, and large organic residues.

2.3. Determination of Soil Physical and Chemical Properties

Standard methods as listed were used to determine soil physical and chemical properties: the hydrometer method was used to determine soil particle size distribution [70]. Organic carbon content was determined using the Walkley-Black method [71], and conversions between organic carbon and organic matter were calculated using the Van Bemmelen factor of 1.724, based on the assumption that soil organic matter contains 58% of soil organic C on average. The Kjeldahl method as described by Bremner and Mulvaney [72], was used to estimate total nitrogen (TN), and the core method was used to determine soil bulk density (g/cm^3) [73]. A glass electrode and pH metre were used to measure soil reaction (pH) in distilled water at a soil:water ratio of 1:2.5 [74]. C:N ratio was computed as the ratio of carbon to nitrogen for each soil sample with the formulae below:

$$\text{C : N ratio} = \frac{\text{SOC}(\%)}{\text{TN}(\%)} \tag{1}$$

where C:N ratio is carbon to nitrogen, SOC represents the concentration of carbon (%) in a soil sample, and TN is the concentration of total nitrogen (%) in the soil sample.

2.4. Calculation of Carbon Stocks

Soil C and N values obtained with soil depth (0 - 20, 20 - 50, 0 - 50 cm) and BD were used to estimate C and N stocks (kg/m^2) using the model by Grüneberg *et al.* [75] and Poeplau *et al.* [76] as stated in **Equation (2)**. This was used to compute C and N stocks of each layer per unit area for each land-use system [23] [77] [78].

$$C_t\left(\text{kg/m}^2\right) = BD_i \times d_i \times OC_i \times a \tag{2}$$

where C_t is C or N stock of the ith layer in kg/m^2, BD_i is bulk density of the ith layer in kg/m^3, C is the soil carbon content in percentage (%), d_i is the thickness of the ith layer (cm), and 10 is the conversion factor from kg/m^2 to t/ha. Also, a represents the accuracy (±0.005% for C and ±0.001% for N) level of the instrument according to the manufacturer's standards [79].

Total carbon and/or nitrogen stocks (kg/m^2) of all land-use in the study sites were tabulated (**Equation (3)**) as:

$$C_{\text{Total stock}} = C_{\text{Fo}} + C_{\text{SWL}} + C_{\text{GL}} + C_{\text{Fa}} + C_{\text{CL}} \tag{3}$$

where C_{Fo}, C_{SWL}, C_{GL}, C_{Fa} and C_{CL} are carbon stocks for forest soil, woodland savannah, grassland, fallow fields, and cropland (maize fields), respectively.

Variation in soil properties across land use, soil type, and depth was tabulated (**Equation (4)**) using native forest land use and the 0 - 20 cm soil depth as reference groups. The variation (%) for cultivated land-use system and the 0 - 20 cm soil depth for a given soil variable were calculated using **Equation (5)** as:

$$\text{Variation}_{\text{Cropland}}(\%) = \left[\frac{\text{Value}_{\text{Cropland}} - \text{Value}_{\text{Forest}}}{\text{Value}_{\text{Forest}}}\right] \times 100 \tag{4}$$

$$\text{Variation}_{0\text{ - }20\text{ cm}}(\%) = \left[\frac{\text{Value}_{20\text{ - }50\text{ cm}} - \text{Value}_{0\text{ - }20\text{ cm}}}{\text{Value}_{0\text{ - }20\text{ cm}}}\right] \times 100 \tag{5}$$

Soil Deterioration Index (SDI)

Soil deterioration indices were calculated on the assumption that the status of individual soil properties under the identified land-use types (woodland savannah, grassland, fallow, and cropland) were once the same as adjacent soils under natural forest (well-stocked soils) before conversion [80]. The differences between mean values of individual soil properties were compared with values of soil properties under well-stocked natural forest (100%), computed and expressed as a percentage of the mean value of individual soil properties using **Equation (6)**. Finally, percentage values were averaged across all soil properties in land-use systems to calculate the soil deterioration index (SDI) **(Equation (6)**) as adopted by Islam and Weil [81], Toru and Kibret [82] from Adejuwon and Ekanade [80].

$$\text{DI}(\%) = \left[\frac{P_{\text{SL}} - P_{\text{RL}}}{P_{\text{RL}}}\right] \times 100 \tag{6}$$

where P_{SL} is the mean value of individual soil property (P) under specific land use (SL), P_{RL} is the mean value of individual soil property (P) under reference land use (RL), and DI is deterioration index. The cumulative sum obtained gave an SDI for the identified land-use types. The higher the total value, the better the quality and/or health of soil for a particular land-use system.

2.5. Statistical Analysis

The two-way analysis of variance (ANOVA) was used to test significant differences (p-value = 0.05) in soil physical and chemical properties between land-use, soil type, and soil depth. The Pearson correlation coefficient was used to test the relationship between soil properties for the 0 - 20 cm and 20 - 50 cm depths. Multiple comparison of means for each soil variable among land-use, soil type, depth, sand, silt, clay, bulk density, carbon, nitrogen, C/N ratio, and pH were conducted using the Duncan test at $\alpha = 0.05$. Mean separation was computed using the least significant difference method ($p < 0.05$). The values obtained were compared with the least significant difference [83]. All analyses were conducted using GenStat version 12.0 for windows.

3. Results

3.1. Land-Use and Soil Types

Five (5) land-use systems were identified. These are Forest, Woodland savannah, Grassland, Fallow, and Cropland (**Table 2**). The soils of the district are generally deep on the upper, middle, and lower slopes (**Table 3**).

From **Table 3**, soil depth varied from 7 cm in Changnalili series (*Gleyic Plinthosol*) to 215 cm in Damongo series (*Ferric luvisol*). In the top and subsoil, soil texture ranged from sandy loam to sandy clay loam. For depth-wise distribution of soil properties, a representative pedon of each soil: Damongo (*Ferric Luvisol*), Murugu (*Haplic Luvisol*), Bediesi (*Dystric Nitisol*), Sutawa (*Thapto-Plinthic Luvisol*), Tanoso (*Dystric Gleysol*), Kpelesawgu (*Dystric Plinthosol*), and Changnalili (*Gleyic Plinthosol*) series confirmed that these soils were formed from shale and colluvium (sediments).

Table 2. Description of land-use systems identified in the Nkoranza district.

Land use	Description
Forest (Fo)	This land use covers more than 0.5 hectares. It consists of native tree species and vegetation (tall and dense trees). The land is less disturbed. It was used as a reference.
Woodland savannah (SWL)	Savannah vegetation mixed with woodland and grassland ecosystem. It is characterised by trees widely spaced.
Grassland (GL)	Rolling terrain with grasses. The local climate favours the growth of these grasses, and in some cases, a few trees.
Fallow (Fa)	Abandoned farmlands left for about 3 to 5 years or more to recover their fertility.
Cropland (CL)	The land was cropped to maize continuously (ranges from 1 - 10 acres). Characterised by continuous clearing, removal of above-ground biomass (crop residue), and levelling of farm fields.

Source: Tan *et al.* [47].

Table 3. Distribution of soil in the Nkoranza (North & South) districts with reference to the FAO/WRB 2014 classification.

Soil series (FAO/WRB Classification)	No. of Sites	Area (km^2)	Area (%)
Acrisol	11	55.00	2.12
Fluvisols	5	58.66	2.26
Gleysols	17	246.69	9.52
Lixisols	19	1726.70	66.61
Luvisol	10	254.09	9.80
Planosols	6	135.28	5.22
Plinthosol	12	115.67	4.46
Total	80	2592.09	100

3.2. Physical and Chemical Properties of Soils

A comparison of mean differences using the GLM indicated that land use and soil depth significantly affected percentage clay, sand, and silt contents ($p < 0.05$). Clay content ranged from 7.76% to 33.24%. The topsoil recorded 17.67% compared to 22.74% in the subsoil. Percentage sand ranged from 40.40% to 78.04%, with a mean of 63.17%. The observed range of percentage sand values showed a negative strong correlation with clay (−0.75; $p = 0.05$) and SOC (−0.73; $p = 0.05$) for the 0 - 20 cm soil depth (Table 4 and Table 5).

Correlation coefficient (r) revealed a strong relationship between clay and SOC (0.63; $p = 0.05$) in the 0 to 20 cm soil depth. Percentage clay varied in forest (26.37%), fallow (17.50%), grassland (15.77%), cropland (15.70%), and woodland savannah (13.23%). Within soil types, percentage clay was in the order: Acrisol (26.37%), Gleysol (19.78), Luvisol (18.82), Plinthosol (14.08), Fluvisol (14.95), Planosol (14.08), and Lixisol (13.17). Among forest land-use and soil type, clay content was statistically significant between woodland savannah, grassland, fallow, and cropland ($p = 0.05$) (Table 6 and Table 7).

Table 4. Descriptive statistics of soil properties for the 0 - 20 and 20 - 50 cm depth.

Variables	Depth (cm)	Min	Max	Mean	Variance	Skew.	Kurt.	CV (%)
Clay	0 - 20	7.76	33.24	17.67	48.68	0.56	−0.39	39.48
	20 - 50	11.4	43.24	22.74	86.29	0.80	−0.16	40.85
SOC	0 - 20	0.43	2.53	1.26	0.45	0.64	−1.05	53.07
	20 - 50	0.07	1.43	0.72	0.12	0.18	−0.56	23.50
Sand	0 - 20	40.40	78.04	63.17	124.00	−0.43	−0.82	17.63
	20 - 50	31.08	80.04	55.82	172.10	0.01	−0.79	23.50
Silt	0 - 20	7.64	32.36	19.15	55.34	0.20	−1.05	38.84
	20 - 50	7.64	80.00	21.44	0.00	0.13	−0.77	40.33
TN	0 - 20	0.05	0.30	0.15	0.00	0.67	−0.49	45.62
	20 - 50	0.02	0.15	0.09	0.00	−0.57	−0.99	40.33
BD	0 - 20	0.89	1.37	1.12	0.01	−0.09	−0.74	11.47
	20 - 50	0.80	1.55	1.25	0.03	−0.61	0.99	13.84
C:N Ratio	0 - 20	6.10	11.00	8.24	1.97	0.14	−0.98	17.02
	20 - 50	3.50	10.50	7.31	2.68	−0.24	0.07	13.84
pH	0 - 20	4.60	7.00	5.40	0.55	0.10	−0.48	13.75
	20 - 50	5.36	6.90	5.36	0.51	0.29	−0.70	13.32

Abbreviation: SOC, Soil Organic Carbon (%); TN, Total Nitrogen; BD, Bulk Density (g/cm^3); BD, Bulk Density; C:N Ratio, Carbon: Nitrogen ratio; pH, soil pH (1:2.5); Sand (%); Silt (%); Clay (%); Min., minimum; Max., maximum; Skew., skewness; Kurt, kurtosis; CV (%), cumulative variance.

Table 5. Pearson correlation matrix of soil physico-chemical properties for the 0 - 20 and 20 - 50 cm.

Soil Variables	Clay	SOC	Sand	Silt	TN	BD	C: N Ratio	pH
(a) 0 - 20 cm								
Clay	-							
SOC	0.63	-						
Sand	**−0.75**	**−0.73**	-					
Silt	0.19	0.51	**−0.78**	-				
TN	0.54	**0.96**	−0.67	0.49	-			
BD	−0.35	−0.43	0.47	−0.38	−0.43	-		
C: N Ratio	0.51	0.47	−0.47	0.22	0.24	−0.18	-	
pH	0.32	0.26	−0.35	0.22	0.20	−0.50	0.30	-
(b) 20 - 50 cm								
Clay	-							
SOC	0.43	-						
Sand	−0.75	−0.47	-					
Silt	0.07	0.26	**−0.70**	-				
TN	0.38	**0.91**	−0.48	0.32	-			
BD	−0.44	−0.55	0.46	−0.22	−0.48	-		
C: N Ratio	0.32	0.57	−0.24	0.01	0.25	−0.34	-	
pH	0.13	0.02	0.08	−0.27	−0.14	0.18	0.38	-

Boldface factor loadings considered highly weighted. Abbreviation: SOC, Soil Organic Carbon (%); TN, Total Nitrogen; BD, Bulk Density (g/cm^3); BD, Bulk Density; C/N ratio, Carbon: Nitrogen ratio; pH, soil pH (1:2.5); Sand (%); Silt (%); Clay (%).

In general, there was a strong positive correlation between SOC and TN contents for the 0 - 20 cm ($R^2 = 0.89$) and 20 - 50 cm ($R^2 = 0.91$) soil depths. The interaction between land use and soil depth indicated a highly significant difference (0.036; $p < 0.05$) for clay at the 0 - 20 cm depth (Table 8). A statistical difference ($p = 0.05$) was observed between the forest and the other four land-use types for sand at the 0 - 20 cm soil depth (Table 6). However, there was no significant interaction between land use and soil depth (0.815; $p = 0.05$), soil depth and soil type (0.456; $p = 0.05$) for percentage sand in the 20 - 50 cm soil depth (Table 9). Also, the percentage sand for Cropland, Fallow, Woodland savannah, Grassland, and Forest were 69.91%, 69.00%, 66.36%, 63.55%, and 47.04%, respectively. Within soil type, Lixisol, Luvisol, Planosol, Plinthosol, Gleysol, Fluvisol, and Acrisol had 71.15%, 69.54%, 67.46%, 54.96%, 64.63%, 63.18%, and 47.04%, respectively for sand content.

Table 6. Mean values of soil physico-chemical properties with standard deviation in parentheses of land-use types.

Land use	Depth (cm)	Clay	Sand	Silt	BD	pH	SOC	TN	C: N Ratio
Forest	0 - 20	26.37 (6.31)a	47.04 (5.63)b	26.59 (5.47)a	1.00 (0.09)a	6.47 (0.41)a	2.31 (0.16)a	0.26 (0.03)a	8.81 (0.31)a
	20 - 50	35.69 (8.24)a	43.98 (13.01)b	20.33 (7.56)a	1.24 (0.10)a	6.32 (0.43)a	0.85 (0.44)a	0.10 (0.05)ab	8.91 (1.36)a
Woodland savannah	0 - 20	13.23 (3.25)b	66.36 (8.59)a	20.41 (6.64)a	1.14 (0.14)a	5.80 (5.80)a	1.03 (0.26)b	0.12 (0.02)bc	8.07 (1.42)a
	20 - 50	18.55b (6.79)b	55.95 (11.28)ab	25.50 (10.12)a	1.35 (0.16)a	5.85 (1.10)a	0.92 (0.21)b	0.12 (0.01)a	7.20 (1.42)a
Grassland	0 - 20	15.77 (5.98)b	63.55 (10.34)a	20.68 (8.28)ab	1.14 (0.09)a	5.35 (5.35)a	1.43 (0.64)b	0.16 (0.04)b	8.35 (1.74)a
	20 - 50	19.86 (6.00)b	56.14 (9.35)ab	24.00 (4.81)a	1.11 (0.24)a	5.30 (0.72)a	0.85 (0.32)b	0.10 (0.02)ab	7.99 (1.69)a
Fallow	0 - 20	17.50 (7.77)b	69.00 (8.63)a	13.50 (5.83)b	1.12 (0.15)a	6.30 (0.95)a	0.67 (0.21)c	0.10 (0.04)c	6.99 (1.16)a
	20 - 50	20.18 (5.77)b	57.59 (18.35ab	22.23 (12.73)a	1.21 (0.14)a	5.9 (1.62)a	0.55 (0.16)a	0.08 (0.03)ab	7.22 (1.30)a
Cropland	0 - 20	15.50 (4.64)b	69.91 (5.65)a	14.59 (4.96)b	1.19 (0.14)a	5.60 (0.75)a	0.89 (0.34)bc	0.10 (0.04)c	9.02 (1.61)a
	20 - 50	19.4 (19.03)b	65.45 (7.83)a	15.14 (6.23)a	1.33 (0.16)a	5.47 (0.86)a	0.40 (0.36)a	0.06 (0.03)b	5.96 (2.12)a

Abbreviation: SOC, Soil Organic Carbon (%); TN, Total Nitrogen (%); BD, Bulk Density (g/cm^3); pH, soil pH (1:2.5); C:N Ratio, Carbon:Nitrogen Ratio; Sand (%); Silt (%); Clay (%). Different letters indicate significant differences (LSD) among the various land-use types ($p < 0.05$).

Table 7. Mean values of soil physico-chemical properties with standard deviation in parentheses of soil types.

Soil Type	Depth (cm)	Clay	Sand	Silt	BD	pH	SOC	TN	C: N Ratio
Acrisol	0 - 20	26.37 (6.31)a	47.04 (5.63)b	26.59 (5.47)ab	1.00 (0.09)c	6.48 (0.4)a	2.30 (0.16)a	0.26 (0.03)a	8.80 (0.30)ab
	20 - 50	31.37 (11.84)a	48.04 (11.07)a	20.59 (4.20)ab	1.23 (0.16)a	6.18 (0.49)a	1.32 (0.35)a	0.16 (0.04)a	8.18 (0.94)a
Fluvisol	0 - 20	14.95 (7.70)b	63.18 (20.33)ab	21.87 (13.90)a	1.14 (0.09)abc	4.93 (0.61)bc	1.01 (0.31)b	0.12 (0.02)bc	7.31 (1.05)bcd
	20 - 50	14.95 (2.74)b	64.55 (11.93)a	20.50 (11.85)ab	1.32 (0.04)a	5.03 (0.62)b	0.58 (0.10)b	0.08 (0.02)b	7.00 (0.38)ab
Gleysol	0 - 20	19.78 (10.60)ab	64.63 (13.44)ab	15.59 (5.56)a	1.15 (0.12)abc	6.15 (0.17)a	0.72 (0.24)b	0.07 (0.02)c	9.31 (1.16)a
	20 - 50	22.78 (5.18)ab	62.13 (12.39)a	15.09 (6.08)ab	1.35 (0.18)a	6.28 (0.28)a	0.31 (0.28)b	0.04 (0.04)b	6.90 (2.27)ab

Continued

Lixisol	0 - 20	13.17 (2.01)b	71.15 (6.60)a	15.68 (4.68)a	1.24 (0.07)ab	5.15 (0.13)bc	0.92 (0.28)b	0.12 (0.03)bc	6.44 (1.34)d
	20 - 50	20.76 (7.02)ab	64.74 (2.02)a	14.50 (10.04)ab	1.34 (0.42)a	4.95 (0.17)b	0.72 (0.32)b	0.10 (0.03)b	7.25 (0.78)ab
Luvisol	0 - 20	18.82 (6.61)ab	69.54 (10.25)a	11.64 (7.12)a	1.11 (0.04)bc	5.43 (0.48)b	0.94 (0.40)b	0.11 (0.04)bc	8.22 (1.47)abc
	20 - 50	26.82 (6.19)ab	66.04 (8.16)a	7.14 (3.42)b	1.35 (0.09)a	5.33 (0.47)b	0.71 (0.25)b	0.09 (0.04)b	7.85 (1.03)ab
Planosol	0 - 20	14.08 (5.15)b	67.46 (8.63)ab	18.46 (5.50)a	1.32 (0.14)a	4.63 (0.61)c	0.79 (0.15)b	0.12 (0.02)bc	6.54 (0.38)d
	20 - 50	14.03 (5.56)b	67.96 (7.47)a	18.01 (6.16)ab	1.37 (0.11)a	4.85 (0.73)b	0.50 (0.23)b	0.07 (0.22)b	6.49 (0.34)ab
Plinthosol	0 - 20	17.99 (1.89)ab	54.96 (18.18)ab	27.05 (7.55)a	1.20 (0.09)ab	5.10 (0.43)bc	0.87 (0.27)b	0.13 (0.03)b	6.75 (0.61)cd
	20 - 50	16.49 (6.54)b	59.60 (19.16)a	23.91 (13.73)a	1.33 (0.06)a	4.93 (0.33)b	0.55 (0.34)b	0.07 (0.05)b	6.16 (0.44)b

Abbreviation: SOC, soil organic carbon (%); TN, Total Nitrogen (%); BD, Bulk Density (g/cm^3); pH, soil pH (1:2.5); C:N Ratio, Carbon:Nitrogen Ratio; Sand (%); Silt (%); Clay (%). Different letters indicate significant differences (LSD) among the various land-use types ($p < 0.05$).

Table 8. Summary of two-way ANOVA for soil physico-chemical properties as influenced by land use, soil type and soil depth for the 0 - 20 cm depth.

Source	DF	Clay	Sand	Silt	BD	pH	SOC	TN	C: N Ratio
Land use & Soil depth									
Land use (LU)	4	**0.014**	**0.017**	0.092	0.294	0.443	**0.002**	**0.002**	0.199
Depth (D)	1	0.237	**0.054**	0.988	0.573	0.627	0.801	0.465	0.861
LU × D	4	**0.036**	0.232	0.212	0.348	0.919	0.990	0.988	0.644
Error		2.888	5.479	4.373	0.082	0.655	0.272	0.028	0.813
Soil depth & Soil type									
Soil type (ST)	6	0.061	0.266	0.365	**0.032**	**<0.001**	**<0.001**	**<0.001**	**0.014**
Depth (D)	1	0.311	0.123	0.263	0.289	0.403	0.620	0.919	0.411
D × ST	6	0.069	0.523	0.561	0.694	0.345	0.323	0.326	0.920
Error		3.803	10.076	7.522	0.075	0.305	0.173	0.019	0.948

Boldface values represent F values. $p(F) < 0.01$; $p(F) < 0.001$. Abbreviation: SOC, Soil Organic Carbon (%); pH, soil pH (1:2.5); C:N Ratio, Carbon:Nitrogen Ratio; BD, bulk density (g/cm^3); Sand (%); Silt (%); Clay (%).

Table 9. Summary of two-way ANOVA for soil properties as influenced by land use, soil type and soil depth for the 20 - 50 cm depth.

Source	DF	Clay	Sand	Silt	BD	pH	SOC	TN	C: N Ratio
Land use & Soil depth									
Land use (LU)	4	**0.041**	0.456	0.622	0.389	0.576	0.144	0.238	0.346
Depth (D)	1	0.966	0.695	0.732	0.956	0.607	0.875	0.652	0.884
LU × D	4	0.504	0.815	0.676	0.422	0.893	0.523	0.632	0.764
Error		5.033	10.811	6.867	0.124	0.654	0.210	0.027	1.089
Soil depth & Soil type									
Soil type (ST)	6	0.109	0.436	0.319	0.407	**0.004**	**0.012**	**0.036**	0.394
Depth (D)	1	0.185	0.203	0.593	0.980	0.087	2.060	0.068	0.618
D × ST	6	0.254	0.456	0.546	0.372	0.647	0.539	0.604	0.584
Error		6.086	9.151	9.548	0.252	0.353	0.211	0.028	0.849

Boldface values represent F values. p (F) < 0.01; p (F) < 0.001. Abbreviation: SOC, Soil Organic Carbon (%); pH, soil pH (1:2.5); C:N Ratio, Carbon:Nitrogen Ratio; BD, bulk density (g/cm^3); Sand (%); Silt (%); Clay (%).

A significant difference between forest and cropland ($p = 0.05$) was recorded for silt (%). However, there were no significant interaction between land use and soil depth (0.676; $p = 0.05$), and for soil depth, and soil type (0.546; $0 < 0.05$) at the 20 - 50 cm soil depth. Silt content in land use type ranged from 7.64% to 32.36%. For soil depth, the top and subsoil had 19.15% and 21.44%, respectively for percentage silt. A strong negative correlation was observed between percentage silt and sand (−0.78; $p = 0.05$). For silt (%), within land-use types, Forest recorded 26.59%, followed by Grassland (20.68%), Woodland savannah (20.41%), Cropland (14.59%), and Fallow (13.50%). For soil type, silt followed the order: Plinthosol (27.05%) > Acrisol (26.59%) > Fluvisol (21.87%) > Planosol (18.46%) > Lixisol (15.68%) > Gleysol (15.59%) > Luvisol (11.64%). Bulk density had a high significant interaction for soil type ($p = 0.032$; $p < 0.05$). However, there was no significant difference between land-use and soil depth (0.348; $p < 0.05$) and for soil depth and soil type (0.694; $p < 0.05$) (Table 8). Soil BD ranged from 0.89 to 1.37 g/cm^3. In terms of depth, topsoil had 1.12 g/cm^3 while the subsoil recorded 1.25 g/cm^3. Within land-use systems, Forest, Fallow, Grassland, Woodland savannah, and Cropland had 1.00 g/cm^3, 1.12 g/cm^3, 1.14 g/cm^3, 1.14 g/cm^3, and 1.19 g/cm^3, respectively. In soil types, bulk density followed the order: Lixisol > Planosol > Plinthosol > Gleysol > Fluvisol > Luvisol > Acrisol.

The hydrogen ion concentration (pH) ranged from 4.60 to 7.00. The top and subsoils had 5.40 and 5.36, respectively. Mean soil pH values for the five land-use systems was in the order: Forest (6.47) > Fallow (6.30) > Woodland savannah (5.80) > Cropland (5.60) > Grassland (5.35). Within soil types, Acrisol, Fluvisol, Luvisol, Lixisol, Plinthosol, Planosol, and Gleysol were 6.48, 6.15, 5.43, 5.15, 5.10, 4.93, and 4.63, respectively. There was a significant difference in soil pH for all soil type (<0.001; $p < 0.01$) for the 0 - 20 cm and (0.004; $p < 0.01$) for the 20 - 50 cm soil depth (**Table 8** and **Table 9**). The two-way ANOVA indicated that land-use and soil depth significantly affected SOC and TN's contents, carbon-nitrogen ratios, and soil pH ($p < 0.001$). The two factors (land use and soil depth) had a significant interactive effect on clay ($p = 0.036$) for the 0 - 20 cm soil depth (**Table 8**). Also, correlation coefficients (r) revealed a strong positive relationship between SOC and TN ($r = 0.96$: $p < 0.05$) for the 0 - 20 cm and ($r = 0.91$: $p < 0.05$) for the 20 - 50 cm soil depths. The vertical distribution of SOC and TN differed in soils under different land-use systems. The mean SOC and TN contents for the 0 to 20 cm depth were significantly higher ($p < 0.05$) in forest and grassland than in cropland and fallow. Irrespective of land use type, the surface soils of the 0 - 20 cm depth showed higher SOC and TN contents than the 20 - 50 cm soil depth. A high positive significant difference was observed between soil pH, SOC and TN ($p = 0.001$; $p < 0.001$) for soil type under the 0 - 20 cm soil depth (**Table 8**).

Furthermore, SOC ranged from 0.43% to 2.53%. Mean SOC content at the surface layer and in the subsoil were 1.26% and 0.72%, respectively. Also, SOC in land-use systems decreased with depth. In land-use systems, Forest had the highest with 2.31% compared with Cropland (0.89%). Acrisol had the highest value of 2.30% for soil types, and Gleysol had the least with 0.72%. Total nitrogen ranged from 0.05% to 0.30%. The topsoil recorded 0.15%, while the subsoil had 0.09%. It followed the order: Forest > Grassland > Woodland savannah > Fallow = Cropland within land-use types. The C/N ratio ranged from 6.10 to 11.00. For depth distribution, topsoil and subsoil had 8.24 and 7.31, respectively. Within land-use types, mean values were in the order: Cropland > Forest > Grassland > Woodland savannah > fallow. Gleysol recorded the highest for land-use systems with 9.31, while Lixisol had the least (6.44). The conversion of forest to other land-use systems affected carbon-nitrogen ratios significantly ($p = 0.014$; $p < 0.05$) for the 0 - 20 cm soil depth under soil type (**Table 8**). Carbon and nitrogen ratios for the 0 - 20 cm (0.644; $p > 0.05$) and 20 - 50 cm (0.764; $p > 0.05$) soil depths were significantly different among land-use systems and soil depth (**Table 8** and **Table 9**; **Figures 3-8**).

3.3. Carbon and Nitrogen Stocks

3.3.1. In Land-Use Types

Statistically, C and N stocks followed a similar trend. A significant difference between the forest and grassland was recorded for carbon stocks. However, there was no significant difference between fallow and cropland in the 0 - 20 cm soil depth. There was a significant difference between C and N stocks within land-use

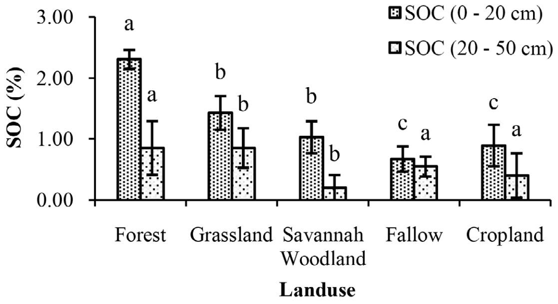

Figure 3. A bar graph with error bars illustrating SOC (%) of land-use system for the 0 - 20 and 20 - 50 cm soil depth. Values assigned the same letters are not statistically different ($p > 0.5$), Duncan's test).

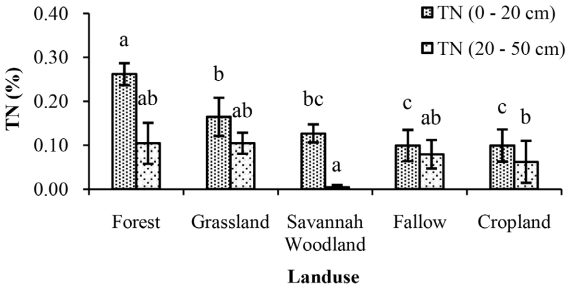

Figure 4. A bar graph with error bars illustrating TN (%) of land-use systems for the 0 - 20 and 20 - 50 cm soil depth. Values assigned the same letters are not statistically different ($p > 0.5$), Duncan's test).

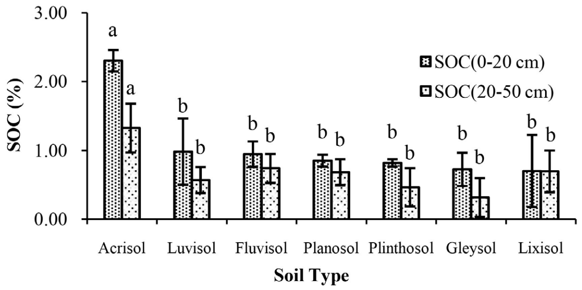

Figure 5. A bar graph with error bars illustrating SOC (%) of soil types for the 0 - 20 and 20 - 50 cm soil depth. Values assigned the same letters are not statistically different ($p > 0.5$), Duncan's test).

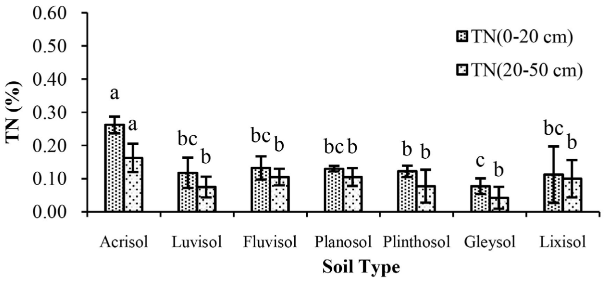

Figure 6. A bar graph with error bars illustrating TN (%) of soil types for the 0 - 20 and 20 - 50 cm soil depth. Values assigned the same letters are not statistically different ($p > 0.5$), Duncan's test).

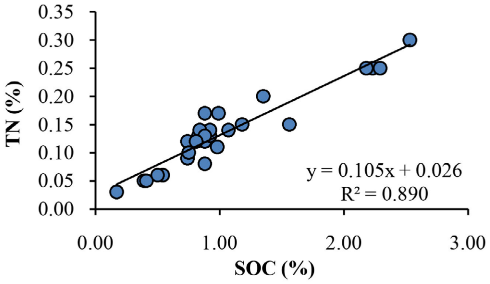

Figure 7. Regression analysis of SOC (%) and TN (%) for the 0 - 20 cm soil depth.

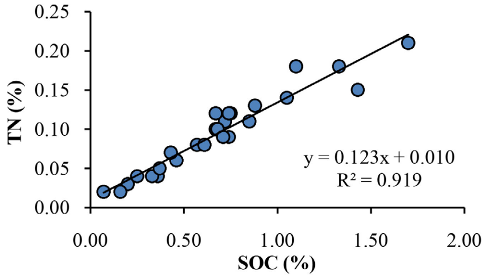

Figure 8. Regression analysis of SOC (%) and TN (%) for the 20 - 50 cm soil depth.

systems and soil types (p = 0.05). In land-use types (Table 10), carbon stocks decreased from 4.63 kg/m^2 to 3.23 kg/m^2 to 2.35 kg/m^2 to 2.11 kg/m^2 and 1.55 kg/m^2 for the forest, grassland, woodland savannah, cropland and fallow for the 0 - 20 cm depth, respectively. Soil carbon in the 20 - 50 cm soil depth followed the order: Woodland savannah > Forest > Grassland > Fallow > Cropland. For nitrogen stocks, 0.52 kg/m^2, 0.37 kg/m^2, 0.28 kg/m^2, 0.26 kg/m^2, and 0.23 kg/m^2 were recorded for forest, grassland, woodland savannah, cropland, fallow, and cropland, respectively for the 0 to 20 cm depth. Nitrogen stocks for the subsoil in land-use types followed the same trend as the 0 - 20 cm depth. Forest had the highest compared to cropland with the lowest in the 0 - 20 and 20 - 50 cm soil depths. A strong positive correlation was observed between C and N stocks for the 0 - 20 and 20 - 50 cm (Table 10; Figures 9-12).

3.3.2. In Soil Types

Within soil types, Lixisol is the most dominant in the Nkoranza District, and it was the most sampled soil type with 19 sites (Table 8). Fluvisol and Planosol each had the least soil sampled sites. Acrisol had the highest carbon (9.60 kg/m^2) and nitrogen (1.13 kg/m^2) stocks, and Gleysol had the lowest for carbon (2.81 kg/m^2) and nitrogen (0.33 kg/m^2) stocks (Table 11). Figure 13 and Figure 14 shows bar graphs indicating the variation of carbon and nitrogen stocks in soil types of the study area. There was a significant interaction between land use and soil depth for nitrogen stocks (0.010; p = 0.05) and between soil depth and soil type for nitrogen (0.031); p = 0.05) in the 0 - 20 cm. However, a comparison between land use and soil depth (p = 0.05) and soil depth and soil type revealed no significant difference among land-use systems for the 20 - 50 cm depth (Table 12).

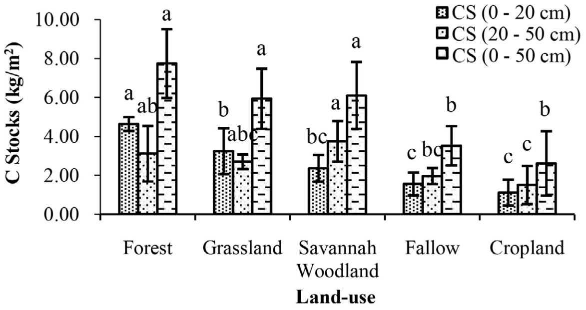

Figure 9. A bar graph with error bars illustrating carbon stocks of land-use system for the 0 - 20, 20 - 50, and 0 - 50 cm soil depth. Values assigned the same letters are not statistically different (p > 0.5), Duncan's test).

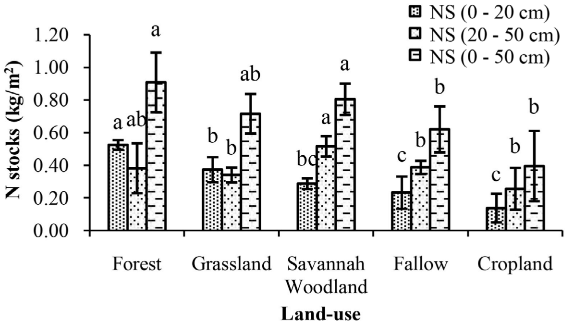

Figure 10. A bar graph with error bars illustrating nitrogen stocks of land-use system for the 0 - 20, 20 - 50, and 0 - 50 cm soil depth. Values assigned the same letters are not statistically different (p > 0.5), Duncan's test).

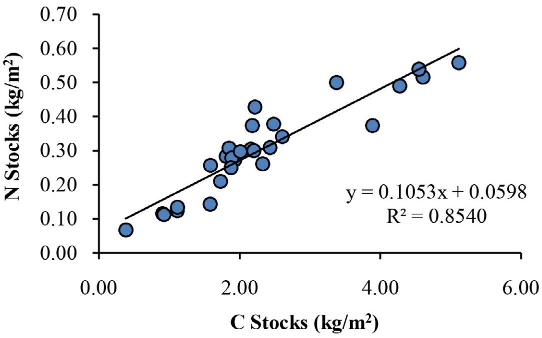

Figure 11. Regression analysis of C and N stocks for the 0 - 20 cm soil depth.

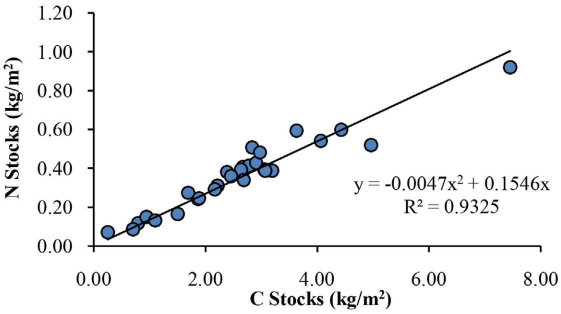

Figure 12. Regression analysis of C and N stocks for the 20 - 50 cm soil depth.

Table 10. Mean carbon and nitrogen stocks (kg/m^2) with standard deviation in parentheses for each land-use in the Nkoranza district.

Land use	**CS (kg/m^2)**	**CS (kg/m^2)**	**CS (kg/m^2)**	**NS (kg/m^2)**	**NS (kg/m^2)**	**NS (kg/m^2)**
	0 - 20 cm	**20 - 50 cm**	**0 - 50 cm**	**0 - 20 cm**	**20 - 50 cm**	**0 - 50 cm**
Forest	4.63 (0.35)a	3.10 (1.42)ab	7.74 (1.25)a	0.52 (0.03)a	0.38 (0.15)ab	0.90 (0.14)a
Woodland Savannah	2.35 (0.68)bc	3.74 (1.04)a	6.10 (1.22)a	0.28 (0.03)bc	0.51 (0.06)a	0.80 (0.07)a
Grassland	3.23 (1.38)b	2.69 (0.43)abc	5.93 (1.81)a	0.37 (0.09)b	0.34 (0.05)b	0.71 (0.11)ab
Fallow	1.55 (0.90)c	2.19 (0.75)bc	3.51 (0.93)b	0.26 (0.09)c	0.31 (0.11)b	0.51 (0.18)b
Cropland	2.11b (0.67)c	1.50 (0.22)c	3.61 (1.76)b	0.23 (0.09)c	0.24 (0.15)b	0.47 (0.22)b
Total	13.87	13.22	26.89	1.66	1.78	3.39

Abbreviation: CS, Carbon Stocks, NS, Nitrogen Stocks. Significant Differences (LSD) among land-use types ($p < 0.05$) are indicated by different letters.

Table 11. Mean carbon and nitrogen stocks (kg/m^2) with standard deviation in parentheses of soil types in the Nkoranza district.

Soil Type (WRB/FAO)	**CS (kg/m^2)**	**CS (kg/m^2)**	**CS (kg/m^2)**	**NS (kg/m^2)**	**NS (kg/m^2)**	**NS (kg/m^2)**
	0 - 20 cm	**20 - 50 cm**	**0 - 50 cm**	**0 - 20 cm**	**20 - 50 cm**	**0 - 50 cm**
Acrisol	4.63 (0.35)a	4.97 (1.84)a	9.60 (2.19)a	0.52 (0.03)a	0.60 (0.22)a	1.13 (0.25)a
Fluvisol	2.13 (0.29b	2.92 (0.80)b	5.05 (1.09)b	0.29 (0.07)b	0.41 (0.10)ab	0.71 (0.16)b
Gleysol	1.53 (0.57)b	1.28 (1.28)b	2.81 (1.81)b	0.16 (0.06)b	0.17 (0.15)b	0.33 (0.21)c
Lixisol	1.72 (1.34)b	2.59 (0.76)b	4.31 (2.11)b	0.27 (0.21)b	0.36 (0.15)b	0.64 (0.37)bc
Luvisol	2.38 (1.23)b	2.30 (0.77)b	4.69 (2.00)b	0.28 (1.23)b	0.30 (0.12)b	0.58 (0.23)bc
Planosol	1.95 (0.38)b	2.35 (0.50)b	4.31 (0.88)b	0.29 (0.05)b	0.36 (0.06)b	0.65 (0.12)bc
Plinthosol	1.90 (0.07)b	1.88 (1.18)b	3.79 (1.25)b	0.28 (0.03)b	0.31 (0.21)b	0.59 (0.23)bc
Total	16.24	18.29	34.56	2.09	2.51	4.63

Abbreviation: CS, Carbon Stocks, NS, Nitrogen Stocks. Different Letters indicate Significant Differences (LSD) among the various land-use types ($p < 0.05$).

Table 12. Summary of two-way ANOVA for carbon and nitrogen stocks as influenced by land use, soil type and soil depth for the 20 - 50 cm depth.

Source	**DF**	**CS (kg/m^2) 0 - 20 cm**	**CS (kg/m^2) 20 - 50 cm**	**CS (kg/m^2) 0 - 50 cm**	**NS (kg/m^2) 0 - 20 cm**	**NS (kg/m^2) 20 - 50 cm**	**NS (kg/m^2) 0 - 50 cm**
Land use & Soil depth							
Land use (LU)	4	**0.012**	**0.047**	**0.016**	**0.010**	0.067	**0.048**
Depth (D)	1	0.797	0.828	0.803	0.256	0.535	0.391
LU × D	4	0.961	0.488	0.969	0.965	0.519	0.923
Error		0.659	0.636	1.046	0.066	0.083	0.133
Soil depth & Soil type							
Soil type (ST)	6	**0.003**	**0.025**	**0.001**	**0.031**	0.090	**0.014**
Depth (D)	1	0.880	0.937	0.901	0.984	0.940	0.962
D × ST	6	0.941	0.683	0.592	0.973	0.734	0.795
Error		0.589	0.852	1.085	0.116	0.121	0.160

Boldface values represent F values. $p(F) < 0.01$; $p(F) < 0.001$. Abbreviation: CS, Carbon Stocks; NS, Nitrogen Stocks.

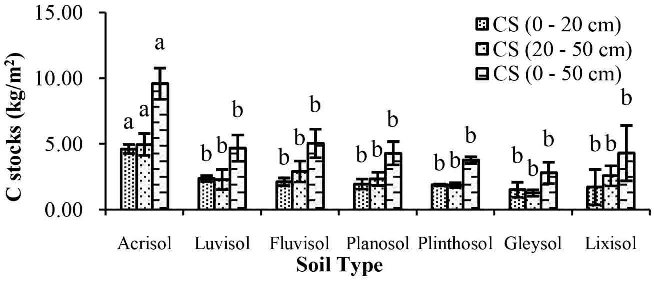

Figure 13. A bar graph with error bars illustrating carbon stocks in soil types for the 0 - 20, 20 - 50, and 0 - 50 cm soil depth. Values assigned the same letters are not statistically different (p > 0.5), Duncan's test).

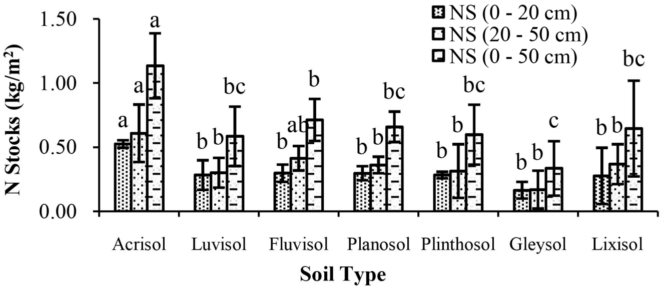

Figure 14. A bar graph with error bars illustration nitrogen stocks in soil types for the 0 - 20, 20 - 50, and 0 - 50 cm soil depth. Values assigned the same letters are not statistically different (p > 0.5), Duncan's test).

3.4. Calculation of Soil Deterioration Indices

In this study, forest, woodland savannah, and grassland had the highest soil organic carbon and total nitrogen content compared to fallow and cropland. Soil deterioration indices of 0%, −17.67%, −23.96%, −25.80%, and −27.99% were recorded for forest, woodland savannah, grassland, fallow and cropland, respectively (Figure 15).

4. Discussion

4.1. Physical and Chemical Properties of Soil

The soils encountered were developed under hydrological conditions along slopes. These geomorphological processes resulted in the formation of different soils from uplands (North-west and South-west) to the lowlands (North-east and South-east section) of the study area. Hence, the formation of various soil associations. For example, Bediesi-sutawa association was associated with upland soils, Damongo-Murugu were associated with middle slope soils, while Kpelesawgu-changnalili association and Tanoso series were attributed to lowland soils [61] [84]. This study reveals that soil is a complex medium that reacts to environmental processes and conditions on the earth's surface. Pedogenic processes ongoing within top and sub-surfaces contribute to the addition, transformation, transfer, and loss of materials [85] [86] in the soils of the study area. Material addition to the top and subsoil are locally derived or transported from elsewhere

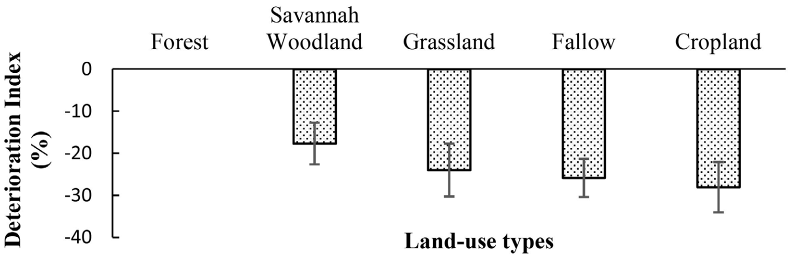

Figure 15. Deterioration index (0 - 20 cm) for different land-use systems in the Nkoranza district.

were in the form of plant litter and animal dropping on the topsoil. For the subsoil, derivatives include plant roots, soil fauna, and microorganisms, and the nature of material transported from the top to the subsoil varied with depth [87] [88]. Leaves and stems carried by running water, dead and decomposing trees, and manure, when added to the soil, support the cultivation of the active topsoil.

From the above discussion, it was observed that there were more additions of soil materials to the topsoil compared to the subsoil, and the transformation of materials (mineralisation) served as plant nutrients [89] [90]. These material additions undergo weathering and/or the formation of clay materials. The weathering process of these soil minerals influences soil chemical characteristics and prevailing environmental factors [86] [91] [92]. These processes reached their height under forests and increased clay minerals with depth (**Table 6**). Materials in the soil were transported within soil layers either in soil solution or suspension [16] [93] [94]. According to Miller and Donahue [95], transported materials appear in solution or as small particles in water draining laterally through the subsoil. Leaching occurred downward, lateral, or in an upward direction, and this facilitated the gradual loss of essential soil nutrients and cations via leaching, thereby increasing soil acidity, as observed in this study [89].

Clay content increased with depth in Acrisol, Gleysol, Lixisol, and Luvisol (**Table 7**). This may be due to eluviation and illuviation processes resulting from the vertical movement of water in the soil. However, rusty and greyish spots associated with abrupt variations of sand and clay contents were observed in the soil [96]. Also, on cropland, as in the case of the maize fields sampled, mechanical transfer of soil properties may have been rapid, lowering soil variability with depth. These mechanical transfers may be due to bioturbation, thus mixing top and subsoil by burrowing animals and through anthropogenic activities [92]. Ploughing of these farmlands mostly mixes soil to a depth of 0 - 20 cm. However, bioturbation effects were lower under forest where additions were through the surface, and these materials remained on the soil for more extended periods [93]. The transformation, transfer, and losses were highest on cropland compared to the other land-use types. This indicates the prevalence of soil quality degradation as more lands are subjected to crop production, which calls for soil nutrient management for maize production [16] [97] in the study area. In summary, the high SOC content and carbon stocks observed in the natural forest compared to cropland are as a result of the frequent addition of litter, presence of roots, and a modified microclimate that favour the decomposition of organic materials in the study area is consistent with the findings of Toru and Kibret [82] and Batlle-Bayer *et al.* [98].

The ratio of carbon to nitrogen (C:N) ratio is a sensitive indicator of soil quality and is also considered an indicator of nitrogen mineralization [99]. Cropland and other land-use systems had a C:N ratio of less than 10. According to Hazelton and Murphy [100], a figure between 10 and 12 is normal for arable soil, and a C:N ratio < 10 indicates a rapid breakdown of organic materials. This implies that the decomposition of organic materials may proceed at the maximum rate possible under tropical conditions [101]. This indicates the incorporation of low organic materials into the soil due to a change in organic material quality. The low C:N ratio could be ascribed to the combination of an increase in organic N compounds due to the introduction of oxygen during tillage and an increase in soil temperature. Also, particle size and soil pH are among several factors that explain the variations observed in C:N ratio under land-use systems [102]. Tellen and Yerima [99] indicated that a low C:N ratio is not conducive to sequestering carbon in the soil.

4.2. Soil C and N Stocks

4.2.1. In Land-Use

The study revealed that soils under forest ecosystems had a significantly higher SOC and TN than cropland soils (**Table 6**; **Figure 2** and **Figure 3**). Soil C concentration influences the retention of nutrients, pH buffering, microbial activity, formation of micro-aggregate and soil structure, water retention or storage, and infiltration [103]. This can be attributed to high organic matter accumulation in tropical forest environments due to increased above and below-ground biomass (root biomass) and lower litter breakdown rates [1] [104]. The findings of this study are consistent with the studies of Delelegn *et al.* [105] and Girmay and Singh [106]. The low SOC and TN values recorded under cropland were due to a decrease in organic materials reverted to the soil system due to high oxidation rates of soil organic matter caused by tillage, which results in organic matter loss owing to water erosion. In addition, the susceptibility of micro-aggregate organic carbon to microbial degradation due to shifting moisture and temperature regimes promoted SOC loss on arable lands [107]. A decrease in carbon stocks was observed between the forest and cropland, which is consistent with the findings of Don *et al.* [108], Fujisaki *et al.* [109], and Bessah *et al.* [46]. The conversion of forests to croplands in the transitional agro-ecological zone has depleted the original amount of SOC, and TN stocks in the 0 - 50 cm (0.50 m) soil layer by 50.77% and 47.77%, respectively. Similarly, SOC and TN stocks were reduced by 20% - 50% [110] and by 34% [111] in the top 0 - 50 cm soil depth when native woodland was cleared to make way for croplands in several studies. According to Detwiler [112], about 58% of SOC and TN loss was found in the upper 0 - 20 cm. This agrees with the findings of Guo and Gifford [113] for tropical soils, which fall within the 30% - 80% range.

The findings of this research indicated higher C and N stocks in the topsoil of the forest than cropland [114] [115] [116] [117], and it also decreased with depth [118]. The decomposition of fallen leaves and dead branches by soil fauna in the soil medium is responsible for the high C and N stocks observed in the forest [119]. This study is consistent with Amanuel *et al.* [120], who observed higher SOC stocks under natural forest compared to other land-use systems in the Bir watershed of Ethiopia. In the forest, the micro-climate required for nutrient transformation is ideal, accelerating the decomposition of organic matter [121]. Furthermore, the abundant fine roots of forest trees are the primary source of carbon and nitrogen additions to the soil [108] [122]. This is carried out through plant root turnover via exudates of mycorrhizal fungi and the rhizosphere [123] [124]. From the above discussion, climate and vegetation are the main soil-forming factors influencing C and N storage in the study area, and this is consistent with the findings of Tsozué *et al.* [91]. Also, SOC is fundamental to the roles played by soil in the provision of ecosystem services (such as carbon sequestration, climate, and greenhouse regulations), nutrient cycling, and provision of services (such as food, fiber, fuel, and water).

4.2.2. In Soil Types

In general, soil C and N stocks were lower in the 20 - 50 cm layers for all land-use systems and soil types (**Table 10**). The increase in C and N stocks in the 0 - 20 cm layer is because it represents the zone of intensive humus formation and fine root development [113] [125] [126] [127]. The highest concentrations of C and N stocks were found in Acrisol (**Table 7**). Acrisols are deep, well-drained, loamy to clay textured, and these features facilitate aggregation and high soil C and N accumulation on well-managed croplands [48]. Acrisols were primarily found on middle slopes and in erosion-prone areas, whereas Fluvisols were found in flat areas [69]. Soils under agriculture had the lowest C and N concentrations in most of the layers of all soil types except Acrisols. Gleysol had the lowest concentration of C and N under fallow land use, and there was no statistical significance among the other four land-use systems (**Table 7**; **Figure 5** and **Figure 6**). There were significantly higher soil C and N concentrations on planosol cultivated to maize, and no significant difference among other soil types except Acrisol under forest. Also, consistent with similar concentrations, trends for all soil types, and land use, C and N were highly correlated (**Table 5**; **Figure 6** and **Figure 7**). Gleysols had the least C and N stocks among the seven soil types because this soil had high sand (64.63%; **Table 7**) content, resulting in low C and N stocks under fallow. Also, low permeability with abrupt textural changes characterised these soils.

Furthermore, some soils were shallow, low in fertility, and had poor drainage (planosol and Plinthosol), making aggregation and organic matter stabilisation difficult [128] [129]. Soils under agriculture confirmed the general global pattern that forest conversion to croplands and grassland results in decreased soil C and

N concentrations [130] [131]. The subsoils mostly have lower C concentration compared to topsoils [132]. The higher C and N concentrations and/or stocks for forest and grassland in the 0 - 20 cm layer may have resulted from the high biomass of fine roots of trees and different grass species for forest and grassland [133]. This resulted in high C concentration in the superficial layers after forest and/or grassland conversion to arable lands. This pattern was observed in the 0 to 10 cm soil layer in a study by Gelaw *et al.* [130] in Ethiopia. Soil carbon variation was accounted for by changes in land use, whereas soil characteristics and environmental variability were accounted for by soil properties and soil type [134]. The low pH observed in the top and subsoils of planosols and Plinthosols (Kpelesawgu and Changnalili series) may have resulted from ferrolysis processes, which explains the segregation of iron oxides (Fe-Mn) and gleying processes [91] [135] [136] [137]. Also, a pH value of < 5.5 was observed in the study area, and this could be due to acidification and breakdown of clay minerals, leaving quartz as the major constituent in the soil medium, as observed by Tsozué *et al.* [91] in Cameroon and by Van Breemen and Buurman [138]. Therefore, SOC is a major soil quality indicator and is an essential driver of most soil processes and functions. From the above discussion, the conversion of forest to human-managed systems reduced SOC content and stocks significantly in soil types [51] [139].

4.3. Effects of Land Use and Soil Type on SOC and TN Concentration and Stocks

A correlation matrix was computed to establish the relationship between measured soil nutrients. From **Table 5**, **Figure 7**, **Figure 8**, **Figure 11** and **Figure 12**, SOC and TN concentrations and stocks were positively correlated with clay. However, sand was negatively correlated with clay and SOC for the top and subsoil depth. Also, the correlation between SOC and TN concentrations and stocks with BD revealed a weak significant negative correlation for the 0 - 20 and 20 - 50 cm soil depths (**Table 5**), is consistent with the findings of Seifu *et al.* [1] and Wang *et al.* [140]. An increase in BD increases soil compaction. This reduces most SOM and SOC services. For example, a reduction in soil water infiltration and drainage capacity causes aeration-related challenges in the soil. Also, BD is closely linked with most soil physical properties and processes such as soil-water dynamics, aeration, mechanical resistance to root growth and development [141]. These explain the significantly high BD values in cropland compared to forest land-use system, which could be due to ploughing, cattle trampling, and the impact of raindrops on unprotected soil [142]. Therefore, it can be deduced that BD was significantly higher in subsoils compared to the topsoils of all land use and within soil types (**Table 6** and **Table 7**). The average BD values of soils (sandy loam) of cropland were found below (1.80 g/cm^3) the rating of Hazelton and Murphy [100] for compact soils.

Also, SOC had a negative significant correlation with bulk density (**Table 5**).

This implies that as SOC increases, bulk density decreases. A low bulk density with an optimum clay content ranges between 10% and 30% is associated with high SOC, resulting in the accumulation of carbon [143] [144]. The larger N stock in Forest and Grassland could be explained by the activity of deep roots, which form pores and assist in transferring nutrients [48] [145]. The large differences observed between C and N stocks in soil types and land use may be attributed to shorter fallow periods of soils under agricultural use. Shallow soils with plinthic properties store less moisture and soil carbon than deep soils. This resulted in low carbon storage in an area with high and irregular rainfall [129]. Six and Paulstian [146] observed that soil physical properties (percentage sand) influence organic carbon by affecting soil aggregate particle-size fraction, bulk density, and soil moisture content (**Table 4**, **Table 6** and **Table 7**) in the study area. Also, grazers such as cattle, sheep, and goats influence lower inputs by feeding on plant species, crop residues and dry leaves. These characteristics are major land-use determinants that influence the establishment of agriculture on deeper and more fertile soils because it is practised with little or no fertiliser application. Also, C and N stocks differ with soil type and land use, and estimates for the entire area accounts for their different proportions on farmers' fields. Considering the proportion of land-use and soil types, the total C and N stocks in the study area were estimated to be 34.56 kg/m^2 and 4.63 kg/m^2, which is equivalent to 345.60 t/ha and 46.30 t/ha, for soil type and 26.89 kg/m^2 and 3.39 kg/m^2 (equivalent to 268.90 t/ha and 33.90 t/ha) for land use types, respectively for the 0 to 50 cm (0.50 m) soil depth.

4.4. Soil Deterioration Index (SDI)

This study proves that soil quality and/or fertility deterioration occurs when soils under forest systems are degraded or converted to agricultural uses without adopting appropriate soil and water management practices. The SDI shows that the conversion from a natural forest into a managed ecosystem in the form of grassland and cropland resulted in a net degradation of soil C and N stocks and other essential soil nutrients (**Figure 15**). A low SDI was observed on cultivated fields compared to other land-use systems. The results of this study indicated that most of the small-scale farm practices are highly exploitative [82] [147]. This affects the potential of cropland to sequester and/or capture atmospheric carbon, which can mitigate climate change in the long term [148]. The results stress that alternative land use with appropriate management strategies such as climate-smart agriculture [149] can enhance the potential of these lands to sequester carbon, thereby reducing emissions in the atmosphere [16] [77] [82] [139] [150]. Also, appropriate measures can be adopted to increase smallholder farmers' adaptive capacity to changing climate in recent years [14] [151]. This can be achieved by recarbonising soils of agroecosystems [152] at the local, national and global levels using sustainable restoration management practices and marketing strategies to reintegrate smallholder agricultural activities into the global produce and carbon market [153] by policymakers at the international community (UN, WTO, etc.).

5. Conclusions

This study estimated C and N contents and stocks in land use and soil types at two soil depths (0 - 20 and 20 - 50 cm). The results indicated variations in soil C and N stocks in land use, soil type, and soil depths. Soil C and N dynamics were influenced by inherent soil properties, land-use change, and management systems. Generally, the high C and N stocks observed in forest and grassland can be attributed to high litter decomposition, and carbon turnover served as C sink with the adoption of best or recommended management practice. Bulk density values were low due to fewer anthropogenic activities, high litter fall, and organic accumulation. This indicated good management practices that improved soil organic carbon sequestration in Forest, grasslands, and Woodland savannah. Smallholder farmers in Nkoranza can sustain their livelihoods by adopting simple soil management techniques (such as crop rotation, growing of cover crops, mulch, compost, fertilization, manure, etc.) for sustainable soil management in the humid Savannah Transition Agro-ecozone of Ghana.

Carbon markets for ecosystem services can contribute additional income and/or incentives to resource-poor farmers to invest in soil management. Recommended management practices (RMP) essential for maintaining and enhancing SOC stocks are needed to improve smallholder food-crop production. This could result in the adoption of management systems that restore depleted SOC stocks due to the conversion of marginal lands into restorative land uses. The estimation of C stocks can be traded at the local level, and this can serve as a baseline to establish a large-scale inventory as a national SOC database for Ghana to assess funds from the Clean Development Mechanism (CMD). This can serve as emission reduction targets for developed and/or industrialized countries under article 12 of the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC).

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Conflicts of Interest

We declare no conflicts of interest regarding the publication of this paper.

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