Research Article

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Soil carbon stock and nutrient characteristics of *Senna siamea* grove in the semi-deciduous forest zone of Ghana

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Abstract: We report soil carbon stock (SCS) and nutrient characteristics of a pure stand of *Senna siamea* grove in comparison with adjacent cropland using *t*-test. This study was conducted in 2018 at the Kwame Nkrumah University of Science and Technology, Kumasi. Soil sampling up to 50 cm depth was carried out from five subplots in each ecosystem. The SCS of the grove at 0–15 cm depth was over 100% greater (30.78 Mg/ha) than that of the cropland (15.16 Mg/ha). Soil pH and total N content of the grove were 5.75 ± 1.22 and 0.10 ± 0.03% in the topsoil (0–15 cm) and 5.52 ± 0.80, 0.06 ± 0.01% and 5.03 ± 1.22, 0.04 ± 0.01% in the 15–30 and 30–50 cm depths, respectively. Although these values were greater in the grove than the cropland, the available phosphorus content was 3–4 fold greater in the latter soil. The two ecosystems affected soil organic carbon and total nitrogen contents significantly ($p < 0.05$) only in the topsoil, but had a significant influence on soil available phosphorus in both the topsoil and the subsoil. Sand content of the grove seemed to explain greater variability in its SCS ($R^2 = 0.81$) than clay content. The greater SCS of the *Senna* grove demonstrates its role in soil carbon storage in tropical climate in the era of climate change.

Keywords: climate change, cropland, ecosystems, land use, soil carbon stock

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1 Introduction

Improper land use and management practices have contributed immensely to extensive land degradation in sub-Saharan Africa and other regions of the world. Land degradation with its associated decline in soil productivity, lack of food security, and recurrent droughts adversely affects millions of livelihood [1] across the globe and has revived the issue of resource sustainability [2].

Land use change often for expansion of agriculture, does not only causes direct habitat and biodiversity loss [3] but also has other effects, such as fragmentation of remaining habitat [4] and eutrophication of water bodies. Carbon emissions from deforestation and other anthropogenic activities including land use change are increasing while the earth's ability to fix the carbon is on the decline by ocean and forest changes [5]. Planting trees, especially quick-growing native species that will not be logged or burned, is a remedial measure through carbon sequestration [5,6]. However, soil carbon stock (SCS) data of such ecosystems to enhance climate change actions and policies are considerably lacking in sub-Saharan Africa. Programs such as Clean Development Mechanism, commenced under the Kyoto protocol, and the reducing emissions from deforestation and forest degradation (REDD+) through the United Nations Framework Convention on Climate Change (UNFCCC) provide financial assistance to support carbon sequestration and reduce greenhouse gas emissions from land use change [7]. This notwithstanding, limited data on SCSs of land use systems are hindering the execution of these mechanisms in tropical countries [8]. More so, despite the general understanding of the impacts of land use change as hazards to agricultural productivity, very few studies quantified the extent, rate, and process of soil nutrient depletion under different land use and management systems in sub-Saharan Africa [6].

Senna siamea is a fast-growing evergreen tree. The tree has a straight trunk and a rounded or irregular and spreading, multi-branched crown with dense folia [9]. Although it is not a nitrogen-fixing species, it is suitable for agroforestry and is used in taungya systems and as shade tree in some agro-ecosystems [10]. It can grow on degraded infertile soils and has many economic uses [11] and presents a potential pathway to increase carbon storage in tropical agro-ecosystems in the era of climate change.

Despite its usefulness in agroforestry and sivicultural systems [10], the few studies on land use systems involving *Senna siamea* in sub-Saharan Africa and elsewhere have not explored comprehensively its impacts on soil properties. For example [12], only measured soil hydrological properties under hedgerow of *Senna siamea* with virtually few or no other direct studies of the tree species on soil properties. The work of [11] in Indonesia only considered the below and aboveground carbon stock of the tree using allometric equations with virtually no data on edaphic characteristics. To bridge this gap, our study aimed to contribute to the understanding of the geochemistry of a pure stand of *Senna siamea* grove by quantifying its SCS and nutrient characteristics in a tropical climate. Given the fact that *Senna siamea* is non-nitrogen-fixing plant, we hypothesized that its contribution to soil nutrient (especially N) status and carbon stock will be comparable to that of a cropland.

2 Materials and methods

The key methodology of the study is summarized in Figure 1.

2.1 Description and location of experimental sites

The study was conducted on two different fields in 2018; the erstwhile Arable Crops Section (06.68589° N, 001.55544° W)

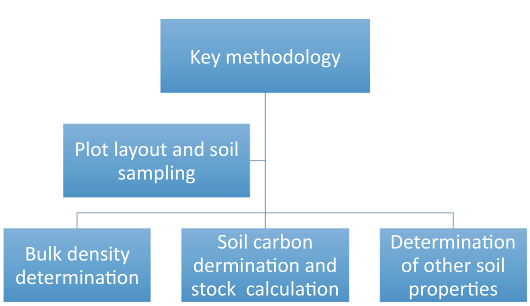

Figure 1: Flowchart of plot layout, soil sampling, and assessment of soil properties.

and the Plantation Crops and Experimentation Section (06.68227° N, 001.55122° W) of the Department of Crop and Soil Sciences, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana (Figure 2).

The Arable Crops Section had been cropped continuously to maize. This led to the establishment of the *Senna siamea* plantation in 1991 for restoration of soil fertility. The grove is relic woodland with pure stand of *Senna* trees up to ca. 30 years of existence. On average, there were six trees per 100 m^2 (10 × 10 m) with diameter at breast height (dbh) ranging from 21 to 110 cm. Dominant grass or weed cover in the grove comprised *Cynodon dactylon*, *Sida acuta*, *Tridax procumbens*, *Pueraria phaseoloides*, *Calopogonium mucunoides*, *Megathyrsus maximus*, *Chromolaena odorata*, *Eleusine indica*, etc. The adjacent cropland has been under cultivation to maize and cowpea for almost 30 years. Notable management practice included application of compound fertilizer (nitrogen, phosphorus and potassium [NPK]) and cereal–-legume rotation practices. The soil type of the study area is Ferric Acrisol.

The experimental sites fall within the moist semi-deciduous forest zone of Ghana characterized by two peak rainy seasons, with a mean rainfall of about 1,500 mm. Temperatures are uniformly high throughout the year, with low and high monthly average of about 25°C and 28°C in August and February, respectively.

2.2 Plots establishment and soil sampling

Five 10 × 10 m plots were demarcated on each site. Five cores of soil samples were collected randomly using auger within each plot at 0–15 cm, 15–30 cm, and 30–50 cm depths. These soil samples were bulked and mixed thoroughly and a composite sample was taken to represent each plot and depth. A total of five composite samples for each depth were obtained from 25 samples per site. The samples were air dried for 2 days and sieved through a 2 mm mesh prior to analysis.

2.3 Soil chemical analysis

Analyses of soil samples were carried out in the Soil Science Laboratory of the Department of Crop and Soil Sciences, KNUST. The soil pH was determined using Suntex pH/Temp (SP-701) meter in a soil:water ratio of 1:2.5. Organic carbon was determined using the Walkley–Black wet

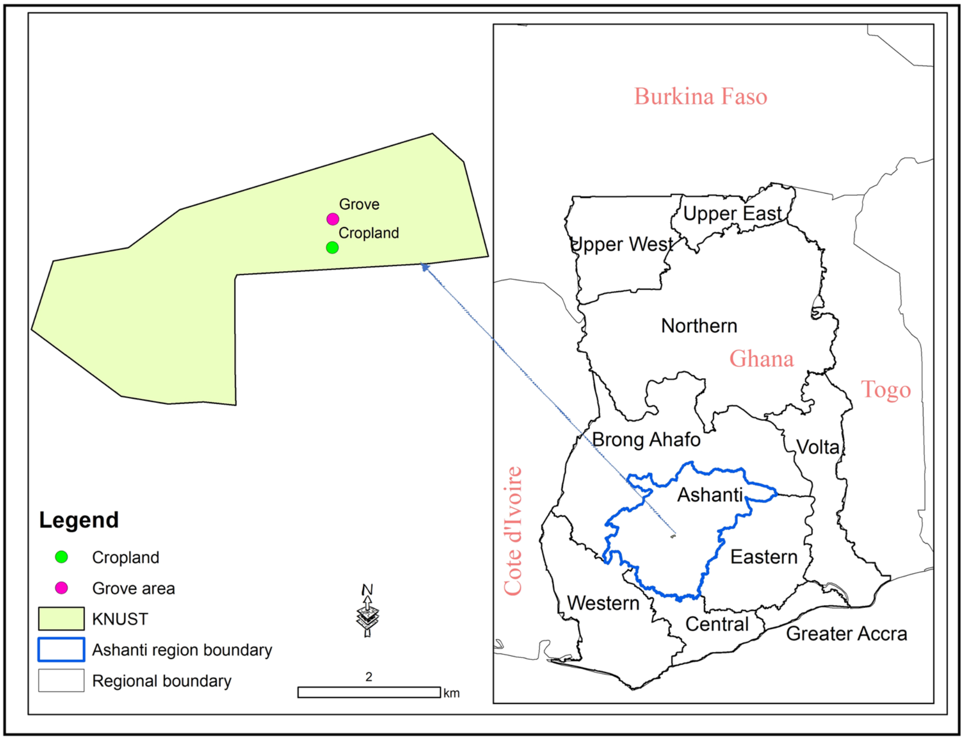

Figure 2: Map showing study area and sites.

oxidation method [13]. Soil total N was determined using the Kjedahl digestion and distillation method [14], while available P was determined by Bray-1 method [15] with the absorbance measured at a wavelength of 650 nm on a double beam spectrophotometer. A 1.0 N ammonium acetate at a pH of 7.0 was used in the extraction of exchangeable bases. Thereafter, potassium and sodium were determined using the flame photometry method, and calcium and magnesium were determined by the EDTA titration method [16]. Aluminum and hydrogen were extracted using 1.0 N KCl. The extract was titrated with 0.05 N NaOH to obtain the exchangeable aluminum. About 4 mL of 3 N NaF was added to the extract before titrating with 0.05 N HCl to a colorless end point to obtain the exchangeable hydrogen [17].

Particle size analysis was carried out using the hydrometer method [18] at two different temperature readings. Soil samples for bulk density determination were taken with a core sampler, weighed, and dried at 105°C for 24 h. Bulk density was determined thereafter from which soil total porosity was calculated.

2.3.1 SCS estimation

The SCS was calculated using the below equation [19]:

$$\mathrm{SCS} = \%\mathrm{OC} \times D \times V \times (1 - g)$$

where SCS, soil carbon stock (Mg/ha); D, soil bulk density; %OC, soil organic carbon content (%); V, volume of soil; g, gravel content.

2.4 Data analysis

Data were analyzed using the student's t-test with GenStat (12th Edition) statistical package. Mean comparison between the two ecosystems was performed at 5% probability.

3 Results

3.1 Soil carbon stock

Figure 3 shows data on SCS of the two land use types. Mean value of SCS of the grove (30.78 Mg/ha) was twice greater than that of the cropland (15.16 Mg/ha). As per results, it is inferable that converting the *Senna* grove to cropland will cause a decline in SCS in the surface soil by over 100%. Sand content of the grove accounted for over 80% (Figure 4) of

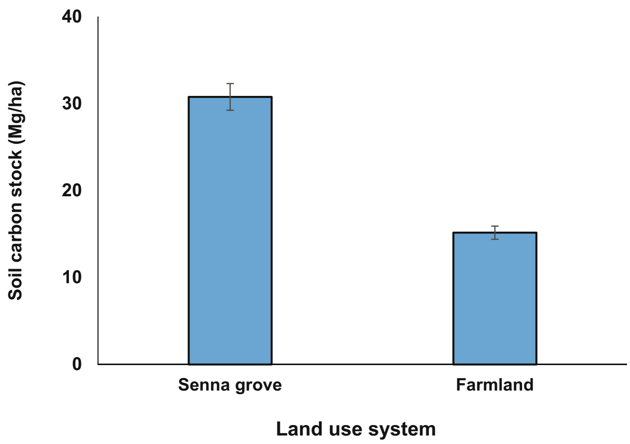

Figure 3: SCS of grove and cropland (farmland) at 0–15 cm depth.

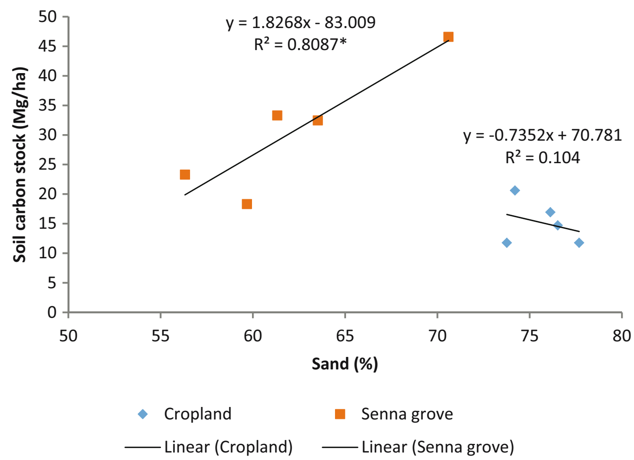

Figure 4: Relationship between SCS and sand content of the two ecosystems; * significant at 5%.

variations in its SCS. SCS showed weak relationship with clay content in both the grove (R^2 = 0.24; Figure 5) and the cropland (R^2 = 0.04). Silt content explained only 1–4% of variations in the SCS of both ecosystems, which were not significant (Figure 6).

3.2 Nutrient status of the *Senna* grove and adjacent cropland

Tables 1–3 show data on soil chemical and physical properties of the two ecosystems. At 0–15 cm depth, soil pH was similar ($p > 0.05$) in the grove and the cropland (Table 1). Similar observations were made at 15–30 cm and 30–50 cm depths. The soil pH ranged from 5.03 ± 0.77 to 5.75 ± 1.22 and 5.27 ± 0.40 to 5.65 ± 0.97, respectively, in the grove and the cropland, being generally higher in the surface soil in both ecosystems.

Soil organic carbon was only significant in the topsoil, being greater (p = 0.05) in the grove than in the cropland. There were no significant differences in soil organic carbon content of the two land use types at deeper depths. Soil organic carbon in the cropland was consistently <1.0% at all depths and also in the deeper depths of the grove. Soil total nitrogen varied from 0.04 ± 0.01% to 0.10 ± 0.03% in the grove and from 0.04 ± 0.01% to 0.06 ± 0.01% in the cropland. The grove and the cropland were significant in soil total N only in the topsoil (0–15 cm) but not in the deeper soil depths. Soil total N content of the grove in the surface soil was greater than that of the cropland. Conversely, soil available P was about four times greater in the topsoil of the cropland than in the grove and about 3

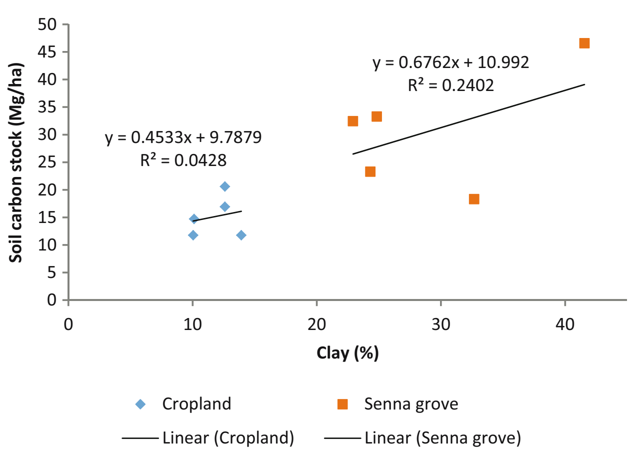

Figure 5: Relationship between SCS and clay content of the two ecosystems.

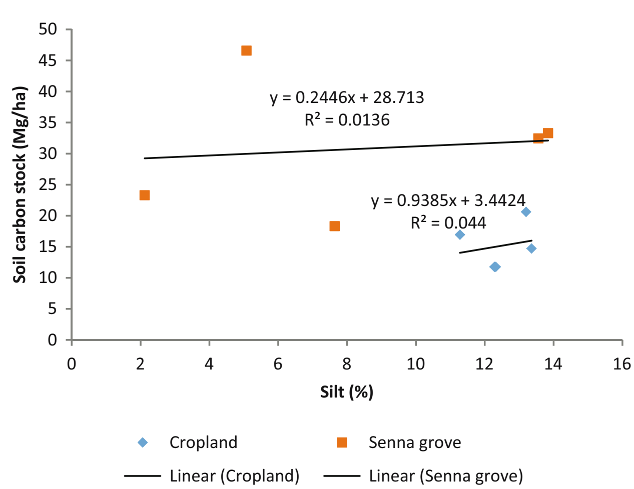

Figure 6: Relationship between SCS and silt content of the two ecosystems.

Table 1: Physico-chemical properties of *Senna* grove and cropland at 0–15 cm depth

Soil properties	*Senna* grove	Cropland	*p*
pH	5.75 ± 1.22	5.65 ± 0.97	0.90
Organic carbon (%)	1.48 ± 0.52	0.82 ± 0.20	0.05*
Total N (%)	0.10 ± 0.03	0.06 ± 0.01	0.02*
Available P (mg/kg)	5.55 ± 0.56	20.05 ± 2.92	0.001*
Exchangeable cations ($cmol_c$/kg)			
Potassium	0.13 ± 0.04	0.08 ± 0.03	0.05*
Calcium	6.52 ± 1.57	3.20 ± 1.87	0.02*
Magnesium	1.92 ± 2.71	1.16 ± 1.18	0.60
Sodium	0.05 ± 0.01	0.04 ± 0.02	0.49
Aluminum	0.27 ± 0.09	0.45 ± 0.07	0.01*
Hydrogen	0.25 ± 0.14	0.22 ± 0.16	0.57
ECEC ($cmol_c$/kg)	8.88 ± 3.84	4.93 ± 1.70	0.05*
Physical properties			
Sand (%)	62.30 ± 5.33	75.66 ± 1.64	0.003*
Silt (%)	8.45 ± 5.18	12.49 ± 0.84	0.16
Clay (%)	29.25 ± 7.86	11.85 ± 1.70	0.01*
Porosity (%)	47.33 ± 0.88	50.93 ± 0.32	0.05*

Values are means of 5 composite samples from 25 samples; mean values with * shows significance at $p \leq 0.05$; ± standard deviation.

times greater in the subsoil (Tables 1–3). Unlike organic carbon and total N, which showed significant differences only in the topsoil of the grove and the cropland, soil available phosphorus was significant at all depths studied.

Soil exchangeable cations were generally greater in the grove than in the cropland (Tables 1–3). Exchangeable calcium content of the grove ranged from 4.60 ± 1.32 to 6.52 ± 1.57 $cmol_c$/kg being generally about two times greater than in the cropland. Exchangeable potassium in the grove ranged from 0.13 ± 0.04 $cmol_c$/kg in the 0–15 cm depth to 0.06 ± 0.02 $cmol_c$/kg at 30–50 cm. Exchangeable sodium content was consistently similar between the grove and the cropland at all depths. Effective cation exchange capacity (ECEC) of the grove and the cropland was generally low (<10 $cmol_c$/kg) and is typical of most soils in sub-Saharan Africa. Exchangeable aluminum levels were significant between the grove and the cropland at all depths. It ranged from 0.23 ± 0.09 to 0.32 ± 0.09 in the grove and from 0.45 ± 0.07 to 0.49 ± 0.12 $cmol_c$/kg in the cropland. There was no consistent trend in its decline with depth in both ecosystems.

Table 2: Physico-chemical properties of *Senna* grove and cropland at 15–30 cm depth

Soil properties	*Senna* grove	Cropland	*p*
pH	5.52 ± 0.80	5.27 ± 0.40	0.56
Organic carbon (%)	0.93 ± 0.31	0.65 ± 0.06	0.12
Total N (%)	0.06 ± 0.01	0.04 ± 0.01	0.07
Available P (mg/kg)	5.58 ± 0.32	19.25 ± 2.93	0.001*
Exchangeable cations ($cmol_c$/kg)			
Potassium	0.10 ± 0.03	0.09 ± 0.00	0.98
Calcium	6.08 ± 1.70	3.16 ± 1.34	0.02*
Magnesium	3.24 ± 3.19	0.56 ± 0.38	0.14
Sodium	0.05 ± 0.01	0.05 ± 0.03	0.91
Aluminum	0.23 ± 0.09	0.49 ± 0.12	0.01*
Hydrogen	0.33 ± 0.09	0.25 ± 0.08	0.47
ECEC (cmolc/kg)	9.70 ± 4.56	4.35 ± 1.25	0.05*
Physical properties			
Sand (%)	60.65 ± 7.76	74.36 ± 1.75	0.020*
Silt (%)	4.04 ± 1.87	11.74 ± 2.24	0.000*
Clay (%)	35.31 ± 7.10	13.90 ± 3.17	0.001*

Values are means of 5 composite samples from 25 samples; Mean values with * shows significance at $p \leq 0.05$; ± standard deviation.

Table 3: Physico-chemical properties of *Senna* grove and cropland at 30–50 cm depth

Soil properties	*Senna* grove	Cropland	*p*
pH	5.03 ± 1.22	5.54 ± 0.86	0.35
Organic carbon (%)	0.46 ± 0.21	0.40 ± 0.12	0.62
Total N (%)	0.04 ± 0.01	0.04 ± 0.01	0.67
Available P	5.30 ± 0.00	15.36 ± 5.70	0.02*
Exchangeable cations ($cmol_c$/kg)			
Potassium	0.06 ± 0.02	0.06 ± 0.02	1.00
Calcium	4.60 ± 1.32	2.72 ± 0.88	0.03*
Magnesium	1.92 ± 0.94	0.88 ± 0.54	0.08*
Sodium	0.05 ± 0.02	0.04 ± 0.01	0.35
Aluminum	0.32 ± 0.09	0.48 ± 0.09	0.02*
Hydrogen	0.33 ± 0.17	0.25 ± 0.04	0.47
ECEC ($cmol_c$/kg)	6.95 ± 1.00	4.18 ± 0.97	0.001*
Physical properties			
Sand (%)	54.45 ± 1.66	71.53 ± 3.30	0.00*
Silt (%)	6.20 ± 1.92	8.86 ± 2.27	0.08
Clay (%)	39.35 ± 2.39	19.61 ± 5.40	0.00*

Values are means of 5 composite samples from 25 samples; mean values with * shows significance at $p \leq 0.05$; ± standard deviation.

3.3 Soil physical properties

Clay content of the grove was greater ($p < 0.05$) than that of the cropland at all depths. Specifically, it was over 146% greater in the surface soil (0–15 cm depth) in the grove than in the cropland and about 154% and 100% greater in the 15–30 cm and 30–50 cm depths, respectively. Conversely, percent sand was greater in the cropland than in the grove. The sand content of the grove ranged from 54.45 ± 1.66% at the deeper depth (30–50 cm) to 62.30 ± 5.33% in the surface soil. For the cropland, sand content was generally greater than 70% at all depths. Unlike clay and sand, silt content of the grove was generally not different from that of the cropland. The silt content of both ecosystems was less than 15% at all depths. The soil total porosity in the *Senna* grove and the cropland at 0–15 cm depth was 47.33 ± 0.88% and 50.93 ± 0.32%, respectively (Table 1) and were significantly different from each other.

4 Discussion

4.1 Soil organic carbon stock

Mean SCS of the *Senna* grove was greater than that of the cropland (Figure 3). SCS is the interplay between bulk density, soil depth, and organic carbon (SOC) content [19]. As soil sampling was carried out at the same depth (0–15 cm) in both land use types, it is inferable that their SCSs were largely influenced by soil bulk density and the organic carbon contents. The relatively greater SOC content of the grove (Table 1) resulted in its greater SCS possibly due to leaf litter accumulation on the soil surface [20]. As forests develop, input of C from litter increases and stabilizes approximately 30 years after afforestation with canopy closure [21]. Tree litter is known to act as mulch, reduce loss of nutrients by erosion and leaching, and increase soil organic carbon content [22]. The two land use systems had significant impacts on soil organic carbon content only in the surface soil but not in the subsoil, being lower in the latter (Table 1). This notwithstanding, the contribution of deep soil carbon to the global carbon stock cannot be underestimated [23,24]. A study [25] noted that subsoil C is less controlled by anthropogenic activities, land cover and climate than topsoil, but more related to soil inherent properties, such as parent material, soil type, and soil texture. Though the organic carbon contents of both the grove and the cropland were low as per the rating of [26], the results show better promise in its buildup under the grove than in the cropland. The cropland as a result of tillage activities resulting in inversion of soil layers exposes the organic matter to microbial decomposition and loss through increased emissions and other loss pathways.

The strong positive relationship between SCS and sand content (Figure 4) seems to suggest that much of the carbon in the grove was stored in the sand + stable (S + A) aggregate pool [27] with lesser amount in the clay fraction. This may have implications for long-term carbon storage in the grove since carbon stored in the S + A fraction has faster turnover rates [27] than in the silt and clay fraction. In a study [28], it was reported that over 84% of variation in SCS of vegetation across a precipitation gradient in West Africa was explained by sand content. Though many studies have established strong relationship between SOC and clay contents due to the key role of clays in soil physiochemical processes, there is no clear-cut evidence on the role of clays stabilizing SOC [28]. This is by virtue of the fact that clay may be correlated with other factors, not making clear which ones are causative [29]. For example, the effect of clay on SCSs is also influenced by its mineralogy [30]. This notwithstanding, some studies have also reported weak correlations between SOC and clay content [31–33].

The greater SCS of the grove shows that land use change from a silvicultural system to cropland can cause a reduction in soil carbon storage by over 100%. Though the former scenario is environmentally safer through reduction in greenhouse gas emission (CO_2), from socioeconomic viewpoint, the impact on peasant agriculture may contribute to economic loss. This calls for a more robust system of crop management in sub-Saharan Africa (SSA), for example, agroforestry systems [34], which can both meet the economic returns of crop farmers whilst also promoting environmental protection through increased carbon storage in the era of climate change.

4.2 Soil nutrient and physical properties

Although not a nitrogen-fixing tree species, soil total N level of the *Senna* grove in the topsoil was moderate [35]. This may be due to its relatively greater organic carbon content (Table 1) as most nitrogen occurs as part of organic molecules [36]. The bulk of soil N is present in the upper horizon where the bulk of organic matter is located [37]. Unless the soil profile contains a horizon of elevated organic matter or a buried A-horizon, N decreases with depth [38]. The grove's relatively greater soil total N content is also ascribable to deep nutrient capture by which nutrient is taken directly from the soil by deeper plant roots with greater root volume [39].

Soil available phosphorus content of the *Senna* grove at 0–15 cm depth was 5.55 mg/kg, which was low and 20.05 mg/kg in the cropland (Table 1), which was moderate as per the rating in ref. [34]. The relatively greater level in the cropland is attributable to its cropping history, which involved annual application of NPK fertilizer for crop production. According to ref. [40], the bulk of P applied remains in the soil as a result of immobilization by microbial biomass and sorption onto soil colloids [41,42]. In low pH soils, sesquioxides play key roles in retention of soil P through fixation mechanisms [43]. The low available phosphorus content of the grove is reflective of the general situation in most managed and unmanaged ecosystems of SSA where P availability declines with extensive weathering and plant uptake as the soil ages. In this regard, once apatite P weathers out, residual P builds up at the expense of organic and other P forms with iron, aluminium, and calcium phosphates solubility modulating P concentration in solution [44,45].

While significant differences in soil organic carbon and total N in the grove and the cropland were observed only in the topsoil, significant differences in available P were observed throughout the depths sampled (Tables 1–3). This suggests that any management practice that affects phosphorus concentration in the topsoil has the tendency to affect its concentration also in the subsoil. This is clearly established by the trend observed in phosphorus levels in both land use types. For example, the level of the nutrient in the topsoil of the cropland was 20 mg/kg, which remained almost same in the 15–30 cm depth and declined by less than five units at the 30–50 cm depth (Tables 1–3). In the grove, the levels remained somewhat uniformly same across depths. This presupposes and confirms the "leachability" of phosphorus [46] to deeper soil layers to contaminate underground water and underscores the importance of soil organic matter and clay content in holding soil nutrients in the upper soil layers against leaching losses.

The exchangeable calcium content of the *Senna* grove was significantly greater than that of the cropland at all depths (Tables 1–3). Comparing the mean values to the rating in refs. [35,47], the *Senna* grove had moderate levels of the cation at both 0–15 cm and 15–30 cm depths. The cropland had low levels of the nutrient. As exchangeable calcium has important relationship with soil pH in nutrient availability [48], higher pH of the grove was expected. However, the difference in the pH under the two land-use types was not significant.

5 Conclusion

This study shows the importance of *Senna siamea* in soil carbon storage and in enhancing soil nutrient status in tropical climate. The grove had greater SCS and generally greater nutrient status than the cropland. The latter as a result of its cropping history characterized by fertilizer application had greater available phosphorus content. Sand content of the *Senna* grove accounted for greater proportion of variability in its SCS than clay content in the surface soil. The two land-use types affected soil organic carbon and total nitrogen concentrations only in the topsoil but influenced soil available phosphorus in both the topsoil and the subsoil. The greater SCS of the *Senna* grove demonstrates its role in soil carbon storage in tropical climate in the era of climate change.

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Author contributions: This work was collaboration among all authors. Author VL designed the study and supervised its implementation, data collection, and analysis. Author ENT participated in the design of the study and implementation and assisted author VL in addressing reviewers' comments. Authors EYA, JM, EAO, and DA collected data and performed analysis. Author VL drafted the manuscript with support from author EYA. Author VL carried out all correspondences.

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