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IMPACTS OF DIFFERENT LAND USE ON SOIL CARBON STOCKS IN THE NORTHERN SAVANNAH AGRO-ECOLOGICAL ZONE OF GHANA

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ABSTRACT

Soils play a vital role in the fight against climate change by acting as a source or a sink for atmospheric CO_2. Understanding the interactions between different land use systems and soil carbon dynamics is therefore important for climate change mitigation strategies. This project was carried out to assess soil carbon stocks and stock changes from 2014 to 2019 under three different land use types, namely arable land, natural regeneration, and woodlots in the Northern savannah agro-ecological zone of Ghana. 15 sampling plots were permanently established within 10 communities. Soil samples to determine organic carbon content and bulk density were taken at 10 cm intervals down to 40 cm soil depth. The samples were taken within 0.5 x 0.5 m quadrats which were laid diagonally in the sampling plots. Soil bulk density ranged between 1.50 to 1.70 g cm^{-3} and was not significantly different with depth across all land use types, neither was soil organic carbon. Percentage increases in mean soil carbon stocks of 5.14%, 11.21% and 15.34% were recorded in arable land, natural regeneration, and woodlot respectively from 2014 to 2019. However, changes in soil carbon stocks between 2014 and 2019 were not significantly different across land use types. There was also considerable variation in soil carbon stock changes among sample plots under each land use type as well as among different depth intervals. The range of carbon stocks measured in this study was on par with other published studies, but for stronger results the study design should be improved.

Key words: climate change, land use, soil carbon stocks, carbon sequestration

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1. INTRODUCTION

On December 12th, 2015, parties of the UNFCCC reached a milestone agreement in Paris, France to combat climate change (UNFCCC 2015). This was referred to as the Paris Agreement. The Paris Agreement aims at keeping the increasing global average temperature to less than 2°C above pre-industrial levels. It further seeks to encourage mitigation strategies to further regulate the rise to 1.5°C above pre-industrial levels. According to Meinshausen et al. (2009), net greenhouse gas (GHG) emissions need to be limited to 36 Pg CO_2-eq yr^{-1} to achieve this goal. Smith et al. (2014) proposed that this may largely be achieved through soil organic carbon (SOC) sequestration. Soils act as a source or sink of atmospheric $CO_{2\ \text{and}}$ hence play a vital role in the fight against climate change. In terrestrial ecosystems, soils represent the most crucial long-term reservoir for organic carbon (FAO 2017).

Carbon exists in inorganic and organic form in soils. SOC constitutes about 50-60% of soil organic matter (SOM) (Rodeghiero et al. 2009). At a global scale, it is estimated that SOM to a depth of one meter contains approximately 1580 Pg of carbon according to Schimel (1995). In comparison, about 610 and 750 Pg are stored in vegetation and the atmosphere, respectively. Soils contain approximately three times the quantity of carbon in the vegetation biomass on earth (500 Pg C) combined (Lal 2004; IPCC 2007; Tarnocai 2009). According to Janzen (2004), about one-third of the SOC is stored in forests, another third in savannahs and grasslands, with the rest in wetlands, crop lands, and other biomes. SOC is extremely vital in chemical, physical and biological soil processes.

The role of soils as a crucial reservoir for carbon is not permanent. SOC changes with accumulation and decomposition (Schrumpf et al. 2008). This means that carbon is continuously being exchanged between the soil and atmosphere in the form of carbon dioxide (CO_2) and methane (CH_4). Therefore, a net carbon loss from soils may result in a considerable increase in atmospheric CO_2 concentration whilst net accumulation will result in a reduction of CO_2 from the atmosphere (Lal 2004). According to the IPCC (2007), anthropogenic activities such as land use and land use change are increasingly influencing the global carbon cycle. For instance, Marland et al. (2000) reported that the conversion of forests to croplands contributed about 40% (180 - 200 Pg C) of the total human carbon emissions over the last 200 years. Other studies (Kasel & Bennett 2007; Janzen 2006) have also reported significant losses in SOC due to conversion of forest ecosystems to cultivated systems. According to Guo and Gifford (2002), these land use changes lead to soil disturbance and erosion which leads to accelerated SOC decomposition.

In contrast, vegetation development on barren/fallow land has been reported to sequester carbon (Choudhury et al. 2014). Land management practices such as minimum tillage, organic farming, crop rotations, residue management and intercropping have also been reported to enhance carbon sequestration (Ramesh et al. 2019). Srinivasarao et al. (2009) studied the effects of eight crop cropping systems (maize, lowland rice, pearl millet, soybean, finger millet, groundnut, sorghum, and cotton-based cropping systems) under different climate and soil types on different pools of soil organic carbon. They recorded the highest (62.3 Mg C ha^{-1}) and lowest SOC stocks under soybean based and pearl-millet and finger millet-based cropping systems respectively. This means that different cropping systems can have different carbon sequestration potential.

In Ghana, Adu-Bredu et al. (2010) studied the effect of four different land use types: forest, cultivated land, fallow land, and teak (Tectona grandis) plantation on carbon stocks in three agro-ecological zones, namely savannah, semi-deciduous forest, and evergreen forest in Ghana.

They reported that the soil carbon stocks in the different land use types in evergreen forest and semi-deciduous forest were, in increasing order: natural forest > teak plantation > fallow land > cultivated land. The lowest stocks in the evergreen forest and semi-deciduous forest zones were recorded under cultivated land, whilst the lowest stocks in the savannah zone were recorded under teak plantation. They recorded the highest stocks under fallow land in both the semi-deciduous forest and savannah zones, whereas in the evergreen forest the highest carbon stocks were recorded under natural forest. Djagbletey et al. (2018) also investigated how carbon stocks of different soil pools and aboveground biomass was spatially distributed in three forest reserves in the Guinea savannah agro-ecological zone of Ghana. They reported a soil carbon stock range of 4.80 to 12.61 Mg C ha^{-1} in the 0-10 cm depth interval. Another study conducted by Logah et al. (2020) compared soil carbon stocks in a pure stand of Senna siamea grove and an adjacent crop land. They reported that the soil carbon stock in the grove was 100% greater (30.78 Mg C ha^{-1}) than in the crop land (15.16 Mg C ha^{-1}) at 0-15 cm depth. According to Logah et al. (2020), the greater soil carbon stock of the Senna grove shows the role it plays in storing soil carbon under a tropical climate in the period of climate change. Anokye et al. (2021), also reported soil carbon stocks along a 1 m soil profile to be 108.2, 99.0 and 73.5 Mg C ha^{-1} in forestland, palm plantation and arable land, respectively.

Different land management practices unarguably have diverse influences on soil carbon stocks. This supports the need to promote land use and management practices that have the potential to sequester carbon and reduce atmospheric CO_2 emissions to mitigate climate change (Logah et al. 2020; Zomer et al. 2008). Institutions and programmes have been established at both national and global level to investigate the interactions between land use and climate change to develop and adapt mitigation strategies (Garnaut 2008). For example, the Clean Development Mechanism (CDM) programme, which started under the Kyoto Protocol, and the Reducing emissions from deforestation and forest degradation in developing countries (REDD+) framework of the UNFCCC has financial mechanisms to support land use practices that lead to carbon sequestration (Dayamba et al. 2016).

In 2011, the Government of Ghana, with support from the Global Environmental Facility (GEF), through the World Bank started the implementation of the Sustainable land and water management project (SLWMP) in the four Northern regions of Ghana (https://www.thegef.org/project/psg-additional-financing-sustainable-land-and-water-management-project). One of the components of this project aimed at identifying sustainable land management practices. This information would eventually be used to determine payment incentives to landowners to apply sustainable land management practices. To contribute towards the achievement of this project, land management practices were monitored to quantify carbon stocks to then determine payments for environmental service (PES) on best practices. In view of this, a framework for monitoring and sampling was established to quantify carbon stocks in the above-mentioned regions. This project seeks to provide information on soil carbon stock changes under various land management practices in Ghana. Information obtained will aid in decision making related to land use management as well as payments for environmental services (PES) to land users under the SLWM project.

1.1 Objectives

The main objective of this project was to assess soil carbon stocks under three different land use types monitored in the SLWM project, namely arable land, natural regeneration, and woodlots in the Northern savannah agro-ecological zone of Ghana.

The specific objectives of the study were:

(1) To quantify the amount of soil carbon stocks stored under the three different land use types

(2) To assess the changes in soil carbon stocks among the three different land use types from 2014 to 2019

2. METHODS

2.1 Study area

Ghana is located on the Gulf of Guinea in West Africa between latitudes 4°N and 11°N and longitudes 4°W and 2°E (MoFA 2015). Ghana borders with Ivory Coast to the west, Burkina Faso to the North, Togo to the East and the Atlantic Ocean to the South (MoFA 2016). The country has a total land surface area of 243,438 km^2 (MoFA 2016) with an estimated population of about 28.31 million in 2016 (Ghana Statistical Service 2017). Presently, Ghana is divided into 16 administrative regions. It must be stated that, at the time the baseline studies were conducted, Ghana had 10 regions: Upper West, Upper East, Northern, Ashanti, Brong Ahafo, Eastern, Greater Accra, Western, Central and Volta. References will thus be made to these regions in this report.

Ghana is characterised by a sub-tropical warm and humid climate with mean annual rainfall and temperature of 1,187 mm and 26.1^{o}C respectively (MoFA 2016). The country is divided into six distinct agro-ecological zones namely Rain Forest, Deciduous Forest, Transitional Zone, Coastal and Northern Savannah. The Northern Savannah agro-ecological zone is further divided into Guinea and Sudan Savannah (Fig. 1). These six agro-ecological zones are defined and characterized based on soil type, vegetation, and climate.

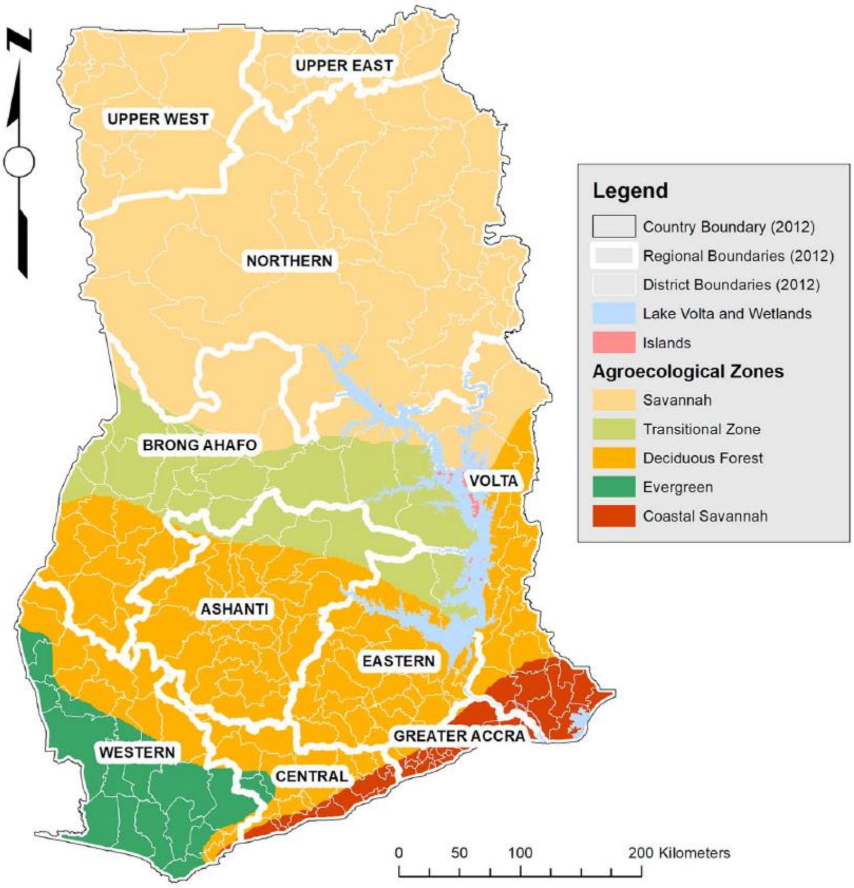

Figure 1. Agro-ecological zones of Ghana: Northern Savannah, Transitional Zone, Deciduous Forest, Evergreen and Coastal Savannah. (Source: Abbam et al. 2018).

This study covers the Northern Savannah agro-ecological zone of Ghana. This agro-ecological zone consists of two of the agro-ecological zones: Guinea and Sudan Savannah. The Guinea Savannah zone covers the Northern and Upper West region. It is characterised by a rainfall season which lasts from May to October. The annual rainfall is about 1,000 mm. The Sudan Savannah covers the north-eastern part of the Upper East region. It has an annual rainfall of 500-700 mm (Issaka et al. 2012). These agro-ecological zones are characterised as dry and very warm with a yearly average temperature of 34°C. According to Issaka et al. (2012) the major soil types in these agro-ecological zones are Savannah Ochrosols (World Reference Base (WRB): Lixisols/Luvisols), Groundwater Laterites (WRB: Plinthosol/Planosol) and Savannah Lithosols (WRB: Lithosols). The Savannah Ochrosols are highly weathered with moderately to strongly acidic topsoil. The soil types in these agro-ecological zones have generally low soil fertility due to low organic matter (<15 g kg^{-1} soil) (Issaka et al. 2012).

The districts in which the studies were conducted are West Mamprusi in the Northern region, Bawku West, Kassena Nankana West, and Talensi in the Upper East region, and Sissala East, Sissala West and Wa East in the Upper West region. The geographical location of the districts and their respective regions is presented in Figure 2 below.

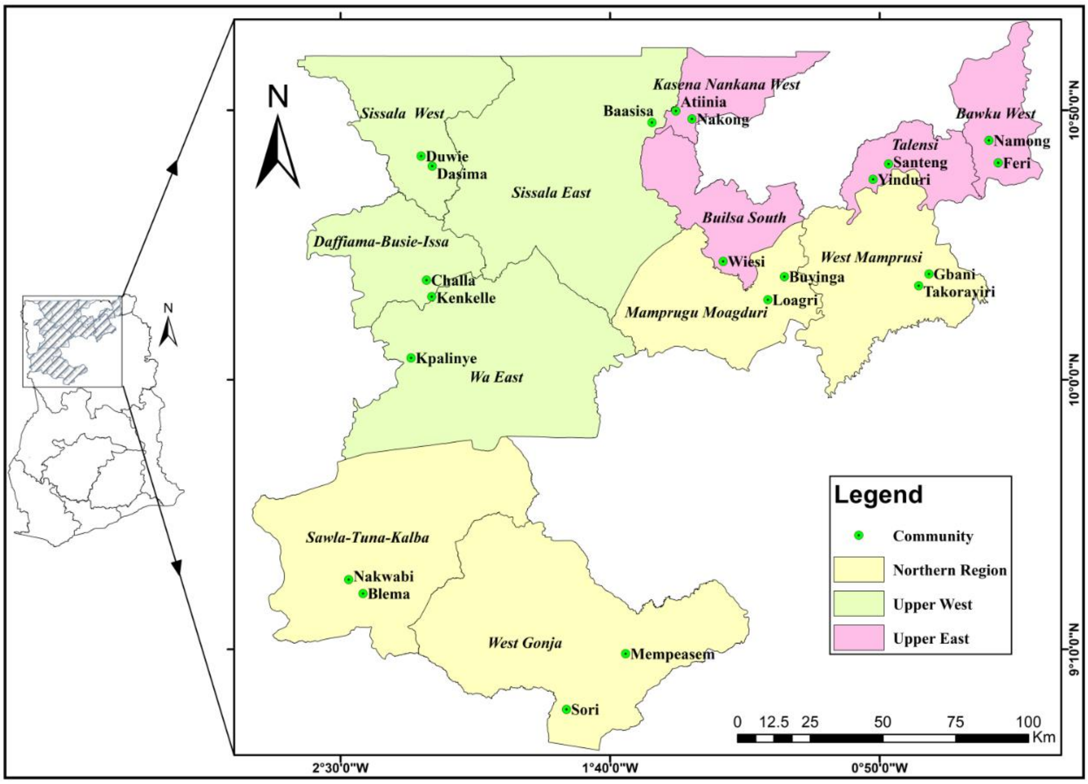

Figure 2. Geographical location of study communities with their respective districts and regions with the image on the left showing the map of Ghana.

A baseline study was carried out between 4th and 15th May 2014. Nine communities were selected from the seven districts. A total of 15 sample plots were permanently established in areas within these communities (Table 1). The elevation of the study sites ranged between 166 and 299 m above sea level. A re-assessment of the same plots was conducted between 8th and 21st August 2019. Details of the regions, districts, and communities where the sample plots were established including the soil types within each district are presented in Table 1.

Table 1. Regions, districts, and communities in which sample plots were established, soil types and number of sample plots per community.

Region	District	Soil type	Community	No. of plots
Northern	West Mamprusi	Cutanic Lixisol	Gbani	2
			Takorayiri	1
Upper East	Bawku West	Pisoplinthic plinthosol, Calci Gleysol	Namong	2
	Kassena Nankana West	Pisoplinthic, Plinthosol, Pisoplinthic gleysol	Atiinia	1
	Talensi	Pisoplinthic Plinthosol	Pwalugu	1
		Gleysol	Santeng	2
Upper West	Sissala East	Arenosol, Pisoplintic Lixisol	Basisan	3
	Sissala West	Gleyic Fluvisol	Dasima	1
		Petric plinthosol	Duwie	1
	Wa East	Pisoplinthic Gleysol	Kpalinye	1

2.2 Study design and sampling

Soil samples were taken under three different land use types: (1) arable land (2) natural regeneration and (3) woodlots (*Senna siamea* and *Acacia* species). The sampling plots for the arable land were laid on maize with either mucuna/pigeon pea/cowpea or soya which were either intercrop or rotation. Adoption of integrated nutrient management was encouraged among farmers. Compost and inorganic fertilizers, specifically N, P and K at a rate of 60 - 30 - 30 kg ha^{-1} N - P_2O_5 - K_2O were recommended. Other land management practices such as weed, and pest control were also recommended. Farmers were encouraged to leave residues on the land instead of burning crop residues after harvesting to enhance soil organic matter build up. The land under natural regeneration had not been under cultivation before the study. Before the start of this project, they were subjected to various land use pressures including unsustainable grazing, bush burning, and tree cutting for fuel production. These land use pressures were discouraged and stopped in agreement with landowners. The areas were then subsequently allowed to undergo natural succession. The areas under natural regeneration did not receive any form of management practice such as fertilizer application, weeding and ploughing. The woodlot areas had been under cultivation until the beginning of this project. As part of this project, farmers were encouraged to establish *Senna siamea* and *Acacia* species which are fast growing and nitrogen fixing trees. The sampling plots for the woodlot land use type were laid on pure woodlots stands. Management practices such as fertilizer application and weed control under this land use type are generally uncommon and was therefore not addressed specifically in this study.

A single plot design of 400 m^2 (20 x 20 m) was employed in the sampling process. The sampling plots were established on the before mentioned land use types in the selected communities (Table 1). Coordinates of the centre of the plots were taken by global positioning system (GPS) to enable re-assessment. The coordinates of the various plots are presented in the Appendix. Three quadrats sized 0.25 m^2 (0.5 x 0.5 m) were laid diagonally in the plot. Two of the quadrats were laid five meters away from each corner of the sample plot. The third quadrat was at the centre diagonal. Soil samples were taken at four different depth levels (0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm) within the quadrats for analysis of organic carbon content and bulk density. For organic carbon analysis, four to five soil samples were taken from each depth and composited (pooled) into one sample per quadrat. One core sample for bulk density analysis was taken from the same soil depths with a core of 5 cm in diameter and 5 cm in height.

2.3 Soil analysis

Bulk density (BD) determination was carried out using a method described by McKenzie et al. (2004). The core samples were oven dried to a constant mass at 105℃ for a minimum of 48 hours. The total sample was weighed, and the coarse fragments (>2 mm) were sieved and weighed separately. The BD was estimated using the method described by
Burt (2004) as follows:

$$BD_{sample} = (ODW - RF - CW) / [CV - (RF/PD)]$$

where: BD_{sample} = Bulk density of the < 2mm fraction (g cm^{-3})
ODW = Oven dry weight
RF = Weight of rock fragments
CW = Weight Empty core
CV = Volume of core

PD = Density of rock fragments

This method determines the bulk density of the fine soil, excluding the gravel. It reflects the weight of the fine earth fraction per core volume for each sample. This is not to be confused with bulk density of the entire soil core, which was not used in this study.

The samples for the organic carbon analysis were air dried and sieved through 2.0 mm mesh. Then, a subsample was taken for the analysis. The soil organic carbon was determined by the modified dichromate oxidation method of Walkley-Black, as described by Nelson and Sommers (1996). Soil organic carbon stocks per unit area for sample plot (*sp*) and stratum (*i*) was determined as described by FAO (2019) as follows:

$$C_{SOCsp,i} = C_{SOCsample,sp,i} \times BD_{sample,sp,I} \times Dep_{sample,sp,i} \times 100$$

where:

$C_{SOCsp,i}$	Carbon stock in SOC for sample plot *sp*, stratum *i*, (Mg C ha^{-1})
$C_{SOCsample,sp,i}$	SOC of the sample in sample plot *sp*, stratum *i*, determined in the laboratory in g C/100 g soil (fine fraction < 2 mm)
$BD_{sample,sp,i}$	Bulk density of fine (< 2 mm) fraction of mineral soil in sample plot *sp*, stratum *i*, determined in the laboratory in g fine fraction cm^{-3} total sample volume
$Dep_{sample,sp,i}$	Depth to which soil sample was collected in sample plot *sp* in stratum *i* (cm)
sp =	1, 2, 3 … *Pi* sample plots in stratum i
i =	1, 2, 3 … *M* strata

The soil bulk density obtained in 2014 was used to calculate soil carbon stocks in both 2014 and 2019. The data on BD from 2019 was deemed faulty due to sampling/analysis errors.

2.4 Statistical analysis

A one-way ANOVA was performed to determine if there were significant differences in BD by soil depth for each land use category. A paired sample t-test was conducted between mean soil carbon stocks in 2014 and 2019. A one-way ANOVA was performed on the change in carbon stocks by land use type as well as the change in carbon stocks by depth for each land use type.

Mean separations were done using the least significant difference (LSD) method at 5% probability level. The assumptions of the statistical tests including normality of data distribution and equality of variance in standard deviation were checked and confirmed before carrying out the analyses. All these analyses were performed using JMP Statistical Software (version 15).

3. RESULTS

3.1 Soil bulk density

The mean soil bulk density (BD) recorded at the four depth intervals for each land use type are presented in Table 2. The soil BD ranged between 1.50 and 1.70 g cm^{-3} and generally increased with depth. There was no significant difference in BD between depth intervals for each land use type (Table 3).

Table 2. Mean soil bulk density of the different land use types in 2014.

Land use type	Soil depth	0-10 cm	10-20 cm	20-30 cm	30-40 cm	No. of sample plots
		Mean soil bulk density (g cm $^{-3}$)				
Arable land		1.58	1.66	1.66	1.70	6
Natural regeneration		1.50	1.57	1.61	1.60	3
Woodlot		1.58	1.67	1.66	1.69	6

Table 3. One-way ANOVA of soil bulk density by soil depth intervals for each land use type.

Land use type	F Ratio	Prob > F
Arable land	1.529	0.238
Natural regeneration	1.530	0.280
Woodlot	1.097	0.374

3.2 Soil organic carbon (SOC)

The mean SOC content of the different land use types for 2014 and 2019 are presented in Table 4. Generally, there was a decreasing trend in mean soil organic carbon with depth under all the land use types. The mean SOC over the entire depth (0-40 cm) was 0.55%, 0.56% and 0.45% for arable land, natural regeneration, and woodlot, respectively for 2014 whilst that of 2019 was 0.59%, 0.63% and 0.53%.

Table 4. Mean SOC of the different land use types for 2014 and 2019.

Land use type	Soil depth	Mean soil carbon content (%)							
		0-10 cm		10-20 cm		20-30 cm		30-40 cm	
	Year	2014	2019	2014	2019	2014	2019	2014	2019
Arable land		0.74	0.95	0.60	0.54	0.59	0.58	0.28	0.30
Natural regeneration		1.04	0.75	0.39	0.59	0.36	0.56	0.45	0.61
Woodlot		0.81	0.88	0.51	0.61	0.26	0.40	0.21	0.23

3.3 Soil carbon stock

The mean soil carbon stocks in the fine soil fraction (< 2 mm) of the different land use types for 2014 and 2019 are presented in Table 5. An increasing trend in soil carbon stocks was recorded at 0-10 cm and 30-40 cm depth intervals under arable land whilst a decreasing trend was observed at 10-20 cm and 30-40 cm from 2014 to 2019. For natural regeneration, a decreasing trend was observed at the 0-10 cm depth interval whilst there was an increasing trend at the other depth intervals. For the woodlot, the soil carbon stocks showed an increasing trend from 2014 to 2019 at all depths.

Table 5. Mean soil carbon stocks in the fine earth fraction (<2 mm) of the different land use types at each depth interval for 2014 and 2019.

Land use type	**Soil depth**	**Mean soil carbon stocks (Mg C ha $^{-1}$)**							
		0-10 cm		**10-20 cm**		**20-30 cm**		**30-40 cm**	
	Year	**2014**	**2019**	**2014**	**2019**	**2014**	**2019**	**2014**	**2019**
Arable land	5	11.76	14.89	9.89	8.90	9.90	9.68	4.78	4.81
Natural regeneration	2	15.60	11.17	6.05	9.18	5.76	8.90	7.14	9.65
Woodlot	5	12.78	13.86	8.54	10.13	4.30	6.63	3.54	3.81

A comparison of the total mean carbon stocks between 2014 and 2019 are presented in Figure 3. A percentage increase in mean soil carbon stocks of 5.14%, 11.21% and 15.34% were recorded in the arable land, natural regeneration, and woodlot respectively from 2014 to 2019.

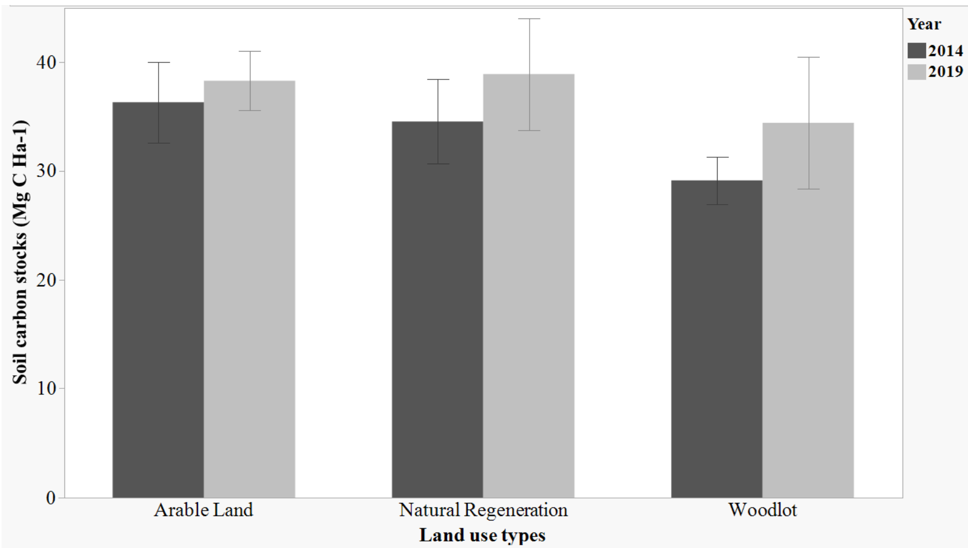

Figure 3. Mean soil carbon stocks (Mg C ha $^{-1}$) of the three land use types for 2014 and 2019. Error bars were constructed using one standard error from the mean.

A paired sample t-test revealed that the difference in soil carbon stock between 2014 and 2019 was not significantly different for any of the land use types (Table 6).

Table 6. Paired sample t-test between mean soil carbon stocks (Mg C ha $^{-1}$) over 0 – 40 cm depth in 2014 to 2019 for each land use type.

Land use type	DF	Std Error	T Ratio	Prob> |t|
Arable land	5	4.437	0.444	0.675
Natural regeneration	2	6.147	0.710	0.552
Woodlot	5	6.454	0.818	0.451

The mean change in carbon stocks between 2014 and 2019 for the sample plots under each land use type is presented in Figure 4. There was considerable variance in the carbon stocks as to whether there was an increase or decrease in carbon stocks even though the mean presents an increase with time. A one-way (ANOVA) revealed that the change in soil carbon stocks between 2014 and 2019 was not significant between land use types (F value = 0.907, n = 15).

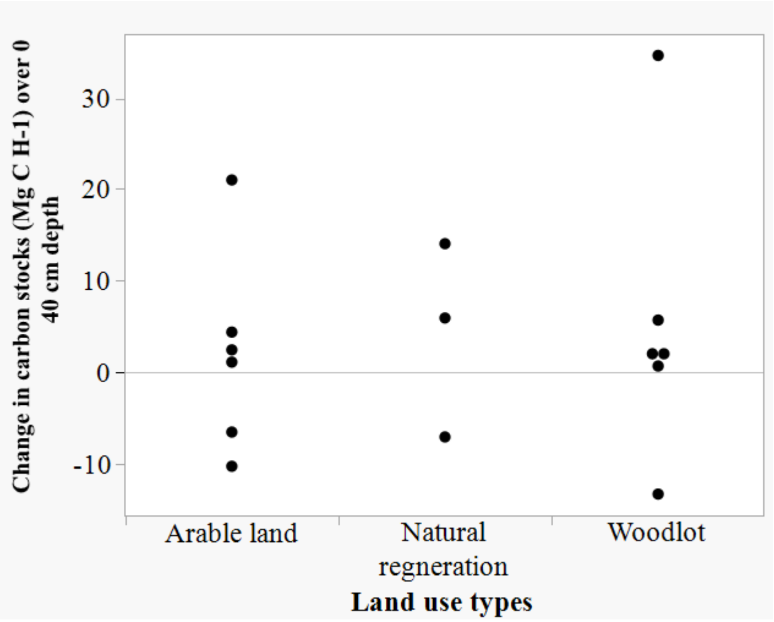

Figure 4. Changes in soil carbon stocks (Mg C ha^{-1}) over 0-40 cm of the sample plots under each land use type.

The mean change in carbon stocks for each depth interval between 2014 and 2019 among the three land use types is presented in Figure 5. A one-way ANOVA of the change in carbon stocks by depth for each land use type was not significant for each land use type (F value = 0.575, 0.199 and 0.912 for arable land, natural regeneration, and woodlot respectively).

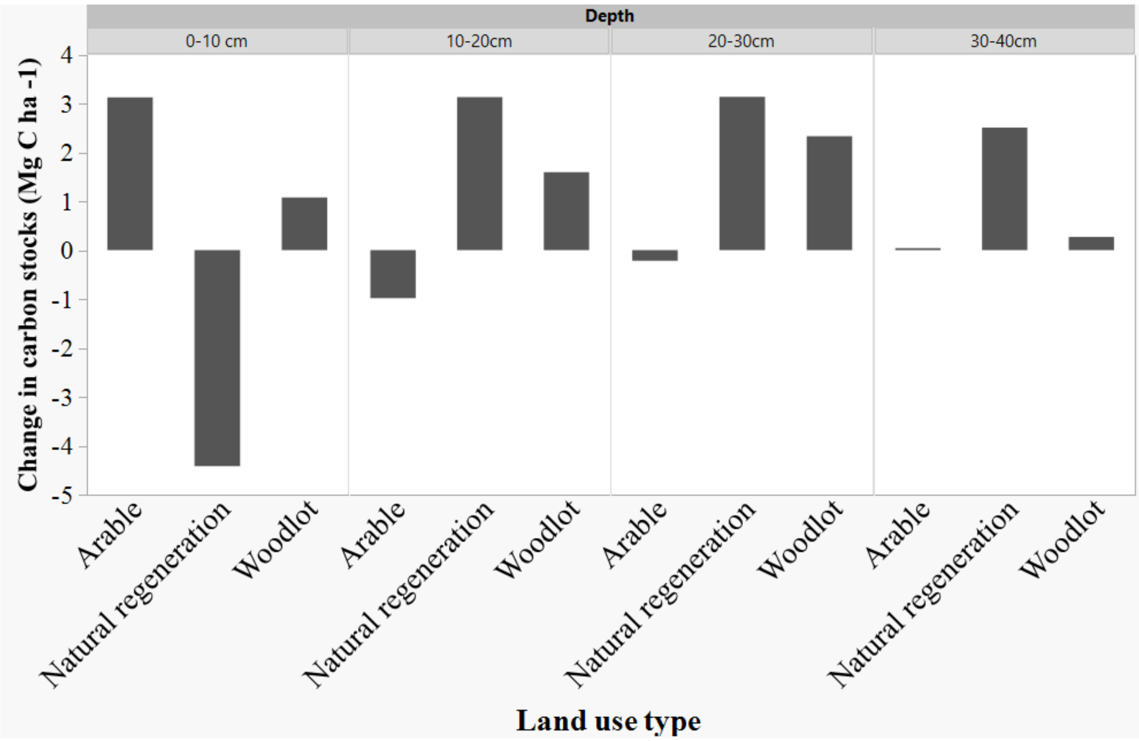

Figure 5. Changes in soil carbon stocks (Mg C ha $^{-1}$) for each depth interval between 2014 and 2019 among the three land use types.

4. DISCUSSION

4.1 Soil bulk density and soil organic carbon

The range of soil bulk density values (1.50 to 1.70 g cm^{-3}) recorded in this study is comparable to the range of 1.15 to 1.89 g cm^{-3} reported by Agyare (2004) within the topsoils (0 – 20 cm depth) in the Tolon/Kumbungu district. Avornyo et al. (2014) also recorded soil bulk density values in a range of 1.2 g cm^{-3} in silt loam soils to 1.5 g cm^{-3} in sandy loam soils around Golinga in the Northern region of Ghana. Bagamsah (2005) also reported a range of 1.3 g cm^{-3} to 1.7 g cm^{-3} at 0 – 10 cm depth in the same region. The range of soil organic carbon values (0.21 – 1.04%) recorded in this study is also comparable to the range of 0.38 – 1.03% reported by Bessah et al. (2016) for the Guinea savannah and Forest-savannah agro-ecological zones of Ghana. According to Adu (1995), the soils in the northern part of Ghana have been reported to be relatively low in terms of soil organic matter content.

Though it was not statistically significant, there seemed to be slightly lower soil bulk density at all depth intervals at the natural regeneration sites compared to arable land and woodlots. Yitbarek et al. (2013) reported that BD values in soils of natural forests were lower than those of cultivated lands in the central and western highlands of Ethiopia.

Furthermore, there seemed to be an increasing trend, however not significant, in BD with depth. This is also widely reported (Abate et al. 2014; Feyissa 2017) and is most often associated with decline in SOM with depth (Pan et al. 2009; Grüneberg et al. 2010; Sharma et al. 2014), which also seemed to be the trend in this study (although not statistically significant). Decreasing soil organic carbon with depth emphasizes the importance of the surface horizon in accumulating and storing carbon (Le Quéré et al. 2015; Hoyle et al. 2013; Lal 2004), as the uppermost layer of soil is where plant residue returns are most concentrated.

The adoption of the management practices like retention of stubble/crop residues instead of burning crop residues during land preparation, minimum/zero tillage, removing grazing pressures etc. was expected to lead to a measurable increase in the accumulation of soil organic matter (Morris et al. 2007). Contributing factors as to why that was not observed could be that management practices were not followed or even that the duration of the study was not long enough for the changes to be fully incorporated. No monitoring system was in place to ensure that land users were following the recommended management practices.

4.2 Soil carbon stocks

The amount of soil carbon stocks recorded in this study, specifically in both the 0-10 and 10-20 cm depth intervals (20.35 to 23.99 Mg C ha^{-1}) across all the land use types in 2014 and 2019 (Table 5) can be compared to the range of 15.33 to 22.89 Mg C ha^{-1} reported by Adu-Bredu et al. (2010) for Ghana's Northern savannah agro-ecological zone. It also corresponds with the range of 11.7 to 41.3 Mg C ha^{-1} observed by Manley et al. (2004) for different land use types that vary in intensities of crop for the 0-20 cm depth for West African savannah regions. Tiessen et al. (1998) also reported an average rate of 25 Mg C ha^{-1} for semi-arid regions. Other studies have reported that soil carbon stocks generally decrease with depth (Soto-Pinto and Aguirre-D´avila 2015; Mohammed et al. 2016) which was an observed trend in this study, although not statistically significant.

The variations observed in the change in soil carbon stocks among the different sample plots across land use types could be attributed to adopted land management practises and site-related factors such as edaphic, biotic, climatic, and topographic factors. Recommended management practices included: (1) maize-cereal intercrop/rotation, integrated soil fertility management, proper residue management under arable land use; and (2) the removal of the land use pressures such as unsustainable grazing, indiscriminate bush burning, and tree cutting for fuel production under both the natural regeneration and woodlot land use type. However, the extent to which farmers adopted these practices is not known and differences in adoption could likely have contributed to the observed variations. An increase in SOC and a build-up was expected on sample plots where these management practices were adopted. Consequently, a decline in soil carbon stocks on sampling plots might mean that these practices where not or poorly adopted.

Furthermore, differing soil types and topographic factors such as elevation with respect to the sample plots could account for some of the observed variations in soil carbon stocks from one location to the other. The amount of SOC varies with soil types depending on soil nutrient status and other soil properties, such as texture and mineralogy. All these factors determine the production of biomass. According to Ramesh et al. (2019), soils that have high nutrient status are characterised by high biomass production and organic carbon sequestration. Concerning mineralogy, soils with 1:1 clay mineral, 2:1 clay mineral, and iron and aluminium oxides and/hydroxides have different specific surface areas and charge densities. These properties dictate the extent of bonding potential between clay minerals and SOC. This interaction between the soil minerals and SOC and dynamics across soil types and ecosystems influences the potential of soil to sequester carbon. Variation in altitude has also been reported to strongly impact on SOC amount regardless of land use (Choudhury et al. 2016). According to Sinoga et al. (2012), SOC increases with elevation because climatic parameters change with elevation. Wang et al. (2010) reported that there could be variations in the horizontal distribution of soil carbon stocks, and this depends to a large extent on macroscale factors such as soil type, topography, vegetation, and regional climate.

The variations observed in the change in soil carbon stocks across depth intervals could be associated with the varied vegetation types which have different rooting patterns as well as allocation of below and above ground biomass. Generally, the amount of plant biomass produced and decomposed determines carbon inputs into the soil profile. Moreover, the amount of plant biomass allocated to above and below ground as well as between root parts could result in clear imprints on how SOC is distributed with soil depth. According to Jobbágy and Jackson (2000) the amount of soil organic carbon may be eclipsed by the effects of plant allocation. They further explained that arid systems are characterised by shrubs with relatively deep root distributions which results in the occurrence of soil carbon deep in the soil profile.

The results show that there were some significant shortcomings regarding the design of the study: the small number of replicates and poorly defined criteria for the differentiation of each land use category, the lack of monitoring of how the land users adopted the recommended management practises, and the short duration of the study. If these shortcomings were to be addressed, I would expect to see more pronounced (and statistically different) changes in carbon stocks with time, as other studies have suggested (Adu-Bredu et al. 2010; Ramesh et al. 2019; Choudhury et al. 2014).

5. CONCLUSIONS AND RECOMMENDATIONS

The results reflected similar BD and SOC values as other studies have reported for similar soil types and regions. The difference in SOC was not significant between 2014 and 2019 for any of the land use types (arable land, natural regeneration, and woodlot). Neither were differences in carbon stocks or changes in carbon stocks. Additionally, there was no significant difference in changes in carbon stocks with depth for any land use type. There were considerable variations in the stock changes within each land use type as well as the stocks within the same depth intervals between different land use types. These results indicate strongly that the study design could be improved upon.

I recommend a more detailed criteria for choosing plots for sampling with well-defined and homogenous land use categories. The same soil type, topography, average rainfall, and temperature should, for example, be important criteria to meet for defining a land use category. I recommend a bigger sample size to be able to better identify statistical differences. I would also recommend preparing a monitoring system to ensure that recommended management practices are followed.

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APPENDIX

No.	Year	District	Community	Plot No.	C Stocks (Mg C Ha^{-1}) 0 - 40cm	Crop/activity	Land use type	Latitude	Longitude	Elevation (m)
1	2014	Kasena Nankana West	Atiinia	32	26.829	*Senna Acacia* Woodlot	Woodlot	10.81351	1.43171	244
2	2019	Kasena Nankana West	Atiinia	32	27.568	*Senna Acacia* Woodlot	Woodlot	10.81351	1.43171	244
3	2014	Sisalla East	Basisan	33	29.847	*Senna Siamea* Woodlot	Woodlot	10.78927	1.49806	222
4	2019	Sisalla East	Basisan	33	16.606	*Senna Siamea* Woodlot	Woodlot	10.78927	1.49806	222
5	2014	Sisalla East	Basisan	34	33.751	*Senna Siamea* Woodlot	Woodlot	10.78683	1.49647	227
6	2019	Sisalla East	Basisan	34	35.635	*Senna Siamea* Woodlot	Woodlot	10.78683	1.49647	227
7	2014	Sisalla East	Basisan	36	20.901	Maize-Mucuna Intercrop	Arable land	10.80315	1.57152	281
8	2019	Sisalla East	Basisan	36	41.959	Maize-Mucuna Intercrop	Arable land	10.80315	1.57152	281
9	2014	Sisalla West	Dasima	38	40.098	Maize-Soya Rotation	Arable land	10.66113	2.21635	291
10	2019	Sisalla West	Dasima	38	41.935	Maize-Soya Rotation	Arable land	10.66113	2.21635	291
11	2014	Sisalla West	Duwie	40	31.768	Maize-Pigeon pea	Arable land	10.6917	2.25099	282
12	2019	Sisalla West	Duwie	40	25.297	Maize-Pigeon pea	Arable land	10.6917	2.25099	282
13	2014	West Mamprusi	Gbani	3	41.001	Natural Regeneration	Natural regeneration	10.33052	0.67672	171
14	2019	West Mamprusi	Gbani	3	33.995	Natural Regeneration	Natural regeneration	10.33052	0.67672	171
15	2014	West Mamprusi	Gbani	6	35.049	Natural Regeneration	Natural regeneration	10.32408	0.68365	153
16	2019	West Mamprusi	Gbani	6	49.149	Natural Regeneration	Natural regeneration	10.32408	0.68365	153
17	2014	Wa East	Kpelinye	42	37.084	Maize-Soya Rotation	Arable land	10.07444	2.27844	273
18	2019	Wa East	Kpelinye	42	41.528	Maize-Soya Rotation	Arable land	10.07444	2.27844	273
19	2014	Bawku West	Namong	12	24.087	*Senna Acacia* Woodlot	Woodlot	10.74215	0.49933	222
20	2019	Bawku West	Namong	12	58.740	*Senna Acacia* Woodlot	Woodlot	10.74215	0.49933	222
21	2014	Bawku West	Namong	14	47.186	Maize-Soya	Arable land	10.74055	0.49362	231
22	2019	Bawku West	Namong	14	36.979	Maize-Soya	Arable land	10.74055	0.49362	231
23	2014	Talensi	Pwalugu	25	36.775	*Senna Siamea* Woodlot	Woodlot	10.60141	0.87234	177

24	2019	Talensi	Pwalugu	25	42.533	*Senna Siamea* Woodlot	Woodlot	10.60141	0.87234	177
25	2014	Talensi	Santeng	19	40.877	Maize-Cowpea Intercrop	Arable land	10.67327	0.79939	161
26	2019	Talensi	Santeng	19	42.047	Maize-Cowpea Intercrop	Arable land	10.67327	0.79939	161
27	2014	Talensi	Santeng	22	27.591	Natural Regeneration	Natural regeneration	10.66462	0.80851	160
28	2019	Talensi	Santeng	22	33.579	Natural Regeneration	Natural regeneration	10.66462	0.80851	160
29	2014	West Mamprusi	Takorayiri	11	23.620	*Senna Acacia* Woodlot	Woodlot	10.28648	0.71588	127
30	2019	West Mamprusi	Takorayiri	11	25.500	*Senna Acacia* Woodlot	Woodlot	10.28648	0.71588	127