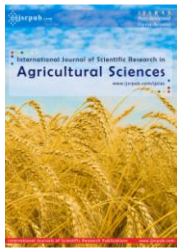
International Journal of Scientific Research in Agricultural Sciences, 1(5), pp. 80-89, 2014
Available online at http://www.ijsrpub.com/ijsras
ISSN: 2345-6795; ©2014 IJSRPUB
http://dx.doi.org/10.12983/ijsras-2014-p0080-0089



Full Length Research Paper

Impact of Aggregate Size on Soil Carbon Sequestration and Aggregate Stability

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Received 19 May 2014; Accepted 18 July 2014

Abstract. Soil aggregation is an important process in carbon sequestration and therefore a useful strategy to mitigate the increase in the concentration of atmospheric CO_2. The study was, carried out on an Acrisol at the KNUST Cocoa (*Theobroma cacao*) plantation. Samples, covered with deep litter, shallow litter and no litter were taken from the 0 – 15 cm depth from three different locations at the sampling site. The organic carbon content and aggregate stability were determined on air – dried samples sieved through graduated sieves into sizes of 0.5 – 1.0 mm, 1.0 – 2.0 mm, 2.0 – 4.0 mm and 4.0 – 6.0 mm using the loss- on- ignition method and modified wet-sieving method, respectively. The study showed that SOC sequestered was highest in the deep litter and the aggregate sizes of 4.0 – 6.0 mm at all sites. The weighted mean of organic carbon for all sizes were 3.02% for deep litter, 2.84% for shallow litter and 1.55% for no litter spots, respectively. The aggregate sizes of 4.0 – 6.0 mm also had the highest stability to external forces. There was also a positive correlation between SOC and aggregate stability. The study confirmed that mature cocoa farms have the potential to store more organic carbon and are relatively stable to reduce erosion and enhance root penetration.

Keywords: Aggregate size, Aggregate stability, Carbon sequestration, CO_2 emission, Soil organic carbon.

1. INTRODUCTION

It is obvious to notice that the evolution of the atmosphere's composition has ultimately affected the development of life on earth. There has been an increase in carbon dioxide amount in the atmosphere. This increase has been the result of fossil-fuel combustion, cement production, and land use change which can be attributed to increasing population and demand for food. However, a probable approach to mitigating rising CO_2 concentrations, quite apart from the development of energy efficient technologies, is improved storage or sequestration of carbon in terrestrial ecosystems (Paustins et al., 1998; Reichle et al., 1999). Sequestration of carbon to reduce atmospheric CO_2 is therefore important. The terrestrial sequestration approach aims at using soil and vegetation to interact as long-term storage pools for atmosphere-derived carbon (Palumbo et al., 2004), thus both plants and soils can provide an attractive mechanism for carbon storage. Carbon sequestration, by definition, is the long term storage of carbon in oceans, soils, vegetation and geologic formations. That of soils and vegetation can be managed by man to increase the length of time it is stored in these materials. The quantity of carbon stored in the soil is highly significant in that it contains about three times the amount of carbon in vegetation and twice the amount in the atmosphere (Batjes and Sombroek, 1997). In this regard, soils are considered as the largest carbon reservoir of the carbon cycle. The ability to capture and secure storage of carbon in soils is a function of depth, texture, structure, rainfall/irrigation, temperature, farming system, soil management and tillage, cropping intensity and nitrogen inputs to soil (Ortega et al., 2002; Lal, 2004; Balanco-Canqui and Lal, 2008; Del-Grosso et al., 2008). Therefore, research and distribution of information on proper land-use and cropping systems to enhance carbon uptake by plants and storage in soils are required (Dowuona and Adjetey, 2010).

According to Brady (2001), soil aggregates are the primary particles that cohere to each other more strongly than other surrounding soil particles. Aggregate formation and stabilization start with organic matter inputs, however, natural levels of soil organic matter are linked to climatic conditions. In view of this, rates of formation may vary with rate of precipitation and temperature (Wright and Hons, 2004). Soil structural attributes such as aggregate type

(Six et al., 2000a), aggregate size and stability (Eynard et al., 2004) may therefore, influence soil organic matter. Elliot (1986) found that carbon concentration increases with increasing aggregate size because large aggregate sizes are composed of micro-aggregates and organic binding agents. Furthermore, younger and more labile organic matter is mostly contained in macro-aggregates. Hence, soil organic carbon associated with aggregates is an important element protected from mineralization because it is less subjected to physical, microbial and enzymatic degradation (Trujilo et al., 1997). Six et al. (1999) reported greater carbon stabilization in no-tillage relative to conventional tillage due to greater amount of macro-aggregates in the former tillage technique. As a result, several studies (e.g. Anger and Giroux, 1996; Spaccini et al., 2001; Onweremadu et al., 2007) have looked into the distribution of soil organic matter in water stable aggregates and their role in aggregate stability.

The relevance of macro-aggregation lies on the positive impact in promoting crop establishment, resistance to erosion and enhanced water infiltration (Angers and Giroux, 1996). However, in most parts of the tropics, soil organic matter losses are high due to high mineralization rate and nutrient losses to soil erosion and leaching (Igwe, 2000) especially when soils are tilled (Onweremadu et al., 2007). Yet, most farmers in the forested agro-ecology hold tenaciously to clean weeding, conventional tillage and slash-and-burn techniques which reduce sequestration of carbon and alter aggregate size (Onweremadu et al., 2010). The objectives of the study, therefore, were to: (i) examine the magnitude of the potential of soils under cocoa plantations in reducing carbon dioxide emissions into the atmosphere, (ii) determine soil organic carbon in different sizes of soil aggregates, (iii) convert the soil organic carbon into equivalent CO_2 and discuss its significance to climate change, (iv) evaluate the importance of cocoa plantation in reducing atmospheric CO_2 and to assess the relation between soil organic carbon and aggregate stability.

2. MATERIALS AND METHODS

2.1. Study area

The study was conducted in the cocoa (*Theobroma cacao*) plantation of the Department of Crop Science. Soil analysis was conducted at the Soil Science Laboratory, of the Department of Crop and Soil science, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana. The area is within semi-deciduous forest zone and is subjected to marked wet and dry season with a bimodal rainfall pattern. The two rainfall peaks make two growing seasons possible. There is heavy rainfall from May to July, which is interrupted by a dry period of about four weeks in August; this is followed by another period of heavy rainfall from September to October. Dry season length is between 120 – 130 days. Annual rainfall is about 1375 mm. Annual temperature ranges from 25 – 35^{o}C. Soils from the area belong to the Asuansi series as described by Adu (1992) or Orthi–Ferric Acrisol FAO (1990) or Typic Haplustult USDA (1998).

2.2. Soil sampling, preparation and analyses

Bulk soil samples were collected from the 0 – 15 cm depth with a spade in a matured cocoa plantation from three different sites based on the extent of litter cover. The various sites were designated as follows, Deep-litter (DL), Shallow litter (SL) and No litter (NL) spots. The samples were air-dried for two weeks, after which they were physically separated into different aggregate sizes of 4 – 6 mm, 2 – 4 mm, 1 – 2 mm and 0.5 – 1 mm with graduated sieves.

2.3. Analytical methods

The particle size distribution of the soils was determined by the hydrometer method (Bouyoucos, 1951). The organic carbon content of the soil samples was determined by loss-on-ignition method (Schulte and Hopkins, 1996). Bulk density was determined with a core sampler (Tuffour et al., 2014). Soil organic carbon was then, converted to CO_2 by multiplying the fraction of SOC by the bulk density of the soil and the depth from which the samples were taken and, converted to tones per hectare. The final result was multiplied by a factor,

$$\frac{44}{12}\ (\text{i.e., } \frac{\text{Molecular weight of } CO_2}{\text{Atomic mass of C}}).$$

The aggregate stability of the soil was determined by the modified-wet-sieving method (Kemper and Rosenau, 1986). Soil pH was determined in water using soil – water ratio of 1:2.5 by a standard pH meter.

3. RESULTS AND DISCUSSIONS

The texture of the soils (Table 1) showed very slight variations and ranges from sand, loamy sand and sandy loam. The pH values were low which was indicative of an acid reaction in the soil. The organic carbon content was highest in the largest aggregate size and lowest in the smallest aggregate size. Aggregate stability was also highest in the largest aggregate size and lowest in the smallest aggregate size. Soil properties of the study area reflected the influence of land use, parent material and climate on soils. In addition to this, Akamigbo (1999) reported marked differences in soil morphological, physical and chemical properties.

Table 1: Mean soil particle and aggregate sizes from the various sampling spots in the field

	Aggregate sizes (mm)			Particle sizes			
				Sand (%)	Silt (%)	Clay (%)	Texture†
Soil samples	Deep litter	0.5-1.0	0.75	84.8	5.2	10	LS
		1.0-2.0	1.50	84.8	5.2	10	LS
		2.0-4.0	3.00	80.8	5.2	14	LS
		4.0-6.0	5.00	80.8	7.2	12	LS
	Shallow litter	0.5-1.0	0.75	74.8	7.2	18	SL
		1.0-2.0	1.50	76.8	7.2	16	LS
		2.0-4.0	3.00	78.8	5.2	16	LS
		4.0-6.0	5.00	76.8	5.2	18	SL
	No litter	0.5-1.0	0.75	84.8	5.2	10	LS
		1.0-2.0	1.50	82.8	5.2	12	LS
		2.0-4.0	3.00	80.8	5.2	14	LS
		4.0-6.0	5.00	70.8	9.2	20	SL

†LS - Loamy sand; SL - Sandy loam

3.1. Particle size and aggregate stability

The sand, silt and clay contents of the different aggregate sizes are presented in Table 2. With the exception of a single location, sand content decreased as aggregate stability increased. Again, silt and clay contents did not follow any consistent pattern with aggregate size (Table 2). Plots of aggregate stability against mean aggregate size for the different sampling locations are presented in Figures 1 - 3. Generally aggregate stability was lowest for the smallest aggregate sizes and highest for the largest aggregate size. However, strong linear relationships existed among aggregate stability and aggregate sizes (Figures 1 - 3). The coefficients of determination for the regression analyses of aggregate stability and aggregate sizes ranged between 0.860 and 0.944. This indicated that aggregate sizes accounted for 86% of the variation in aggregate stability when the site was weedy (Figure 3) and 94.4% when the site was covered with deep cocoa litter fall (Figure 1). At the site with shallow litter fall, aggregate size accounted for 89.3% variation in aggregate stability (Figure 2). According to Elliot (1986), soils that have high silt content often show lower aggregate stability. Boix-Fayos et al. (2001) noted that increases in aggregate stability were related to the silt and clay contents of the soil. In this work too, there was apparent increase in silt plus clay contents as aggregates size increased. In this study, aggregate stability increased with aggregate size. Similar results were found by Bronick (2005) who attributed this to the high clay content binding the aggregates together. However, in this study it was noted that different clay fractions and aggregate sizes affected aggregate stability differently based on thickness of the leaf litter fall. Kemper et al. (1987) reported similar findings.

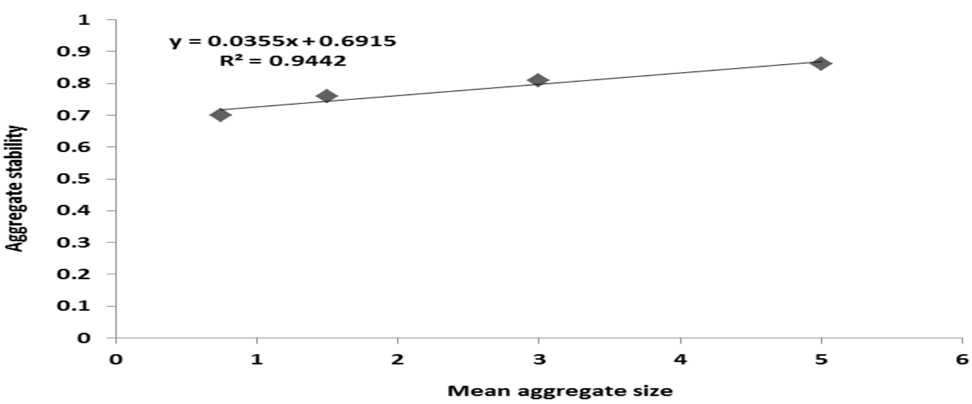

Fig. 1: Plot of aggregate stability against mean aggregate size for deep litter cover

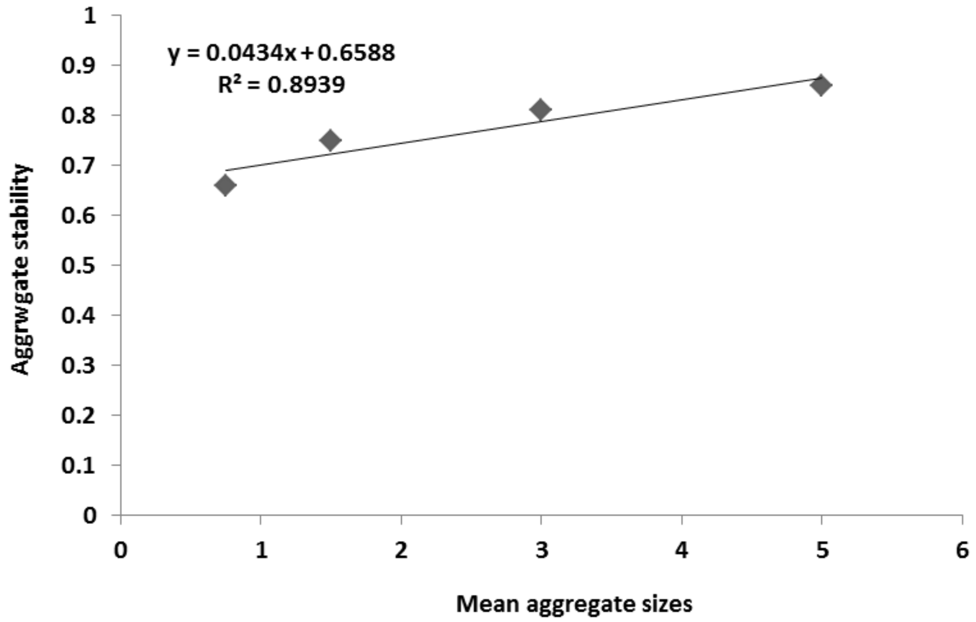

Fig. 2: Plot of aggregate stability against mean aggregate size for shallow litter cover

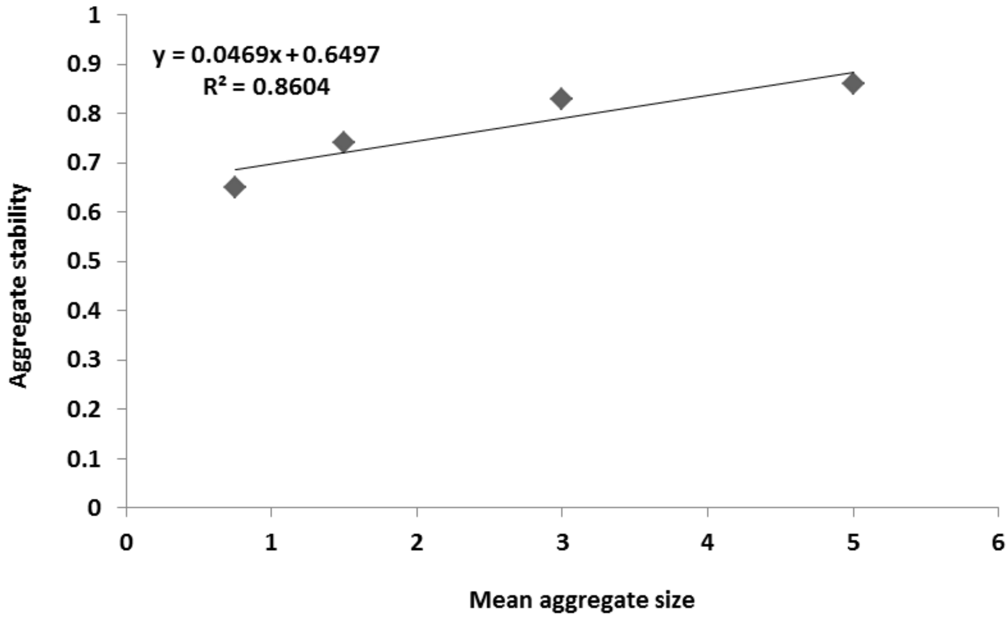

Fig. 3: Plot of aggregate stability against aggregate size in the absence of litter cover

3.2. Aggregate size, soil organic carbon and aggregate stability

Plots of soil organic carbon against mean aggregate sizes for the deep litter location and the weedy (no litter) location are given in Figures 4 and 5, respectively. Positive correlations were found between soil organic carbon and aggregate sizes. As aggregate sizes increased soil organic carbon content increased. Again, there were strong linear relationships between soil organic carbon and aggregate sizes, with coefficient of determination ranging between 0.904 and 0.911 (Figures. 4 and 5). These indicated that between 90.4 and 91.1% variations in soil organic carbon could be ascribed to aggregate sizes. Similar work done by Six et al. (2002) also concluded that organic matter content increased with increasing aggregate sizes.

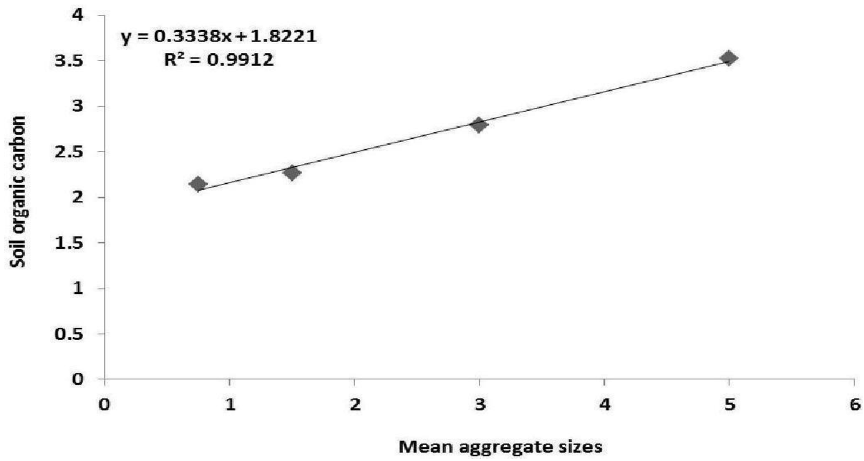

Fig. 4: Correlation of mean aggregate size and soil organic carbon for deep litter soils

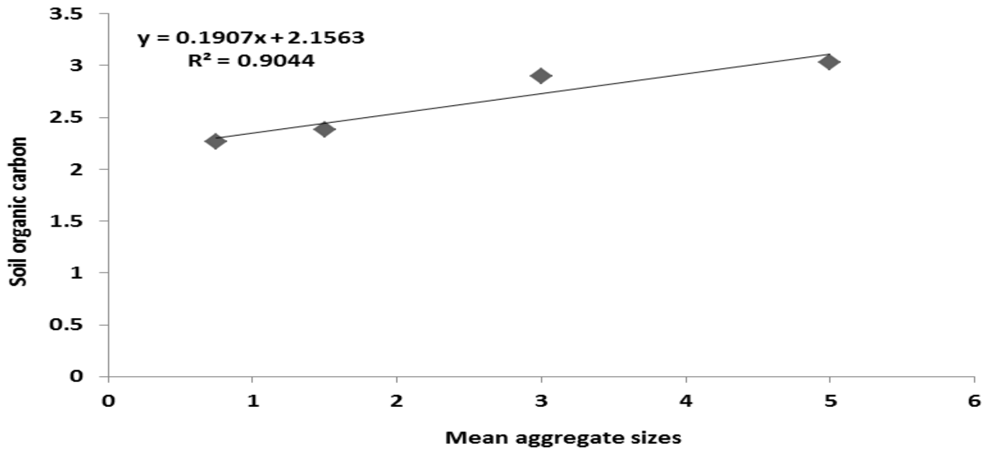

Fig. 5: Correlations between aggregate size and organic carbon in the absence of litter cover

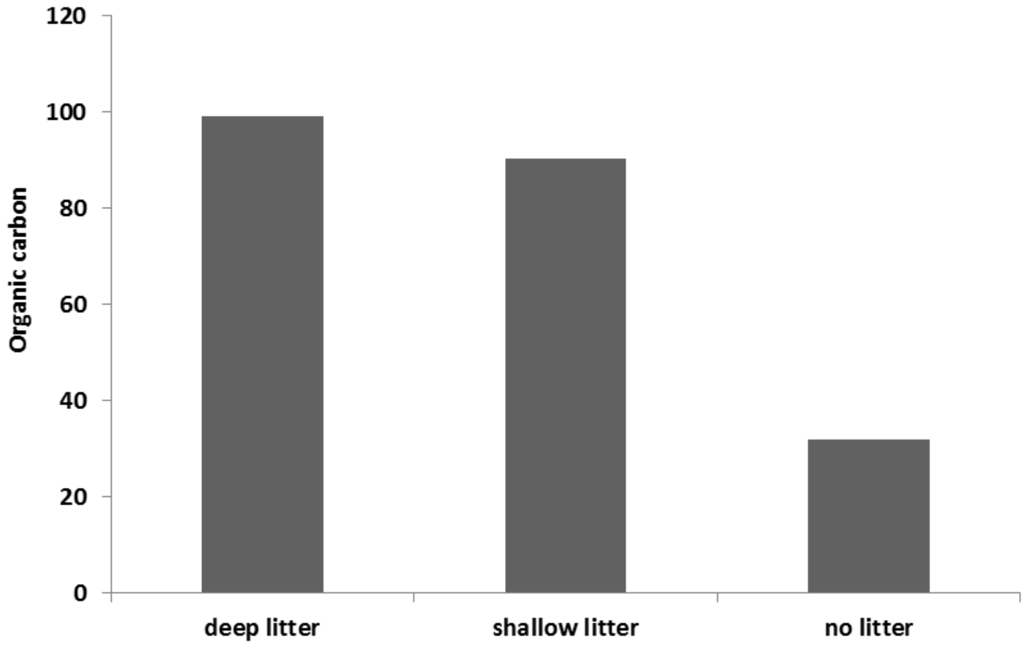

Fig. 6: Weighted mean of organic carbon from different litter sites

3.3. Aggregate stability and its relation to soil organic carbon

The weighted means of soil organic carbon (SOC) from the three sampling sites are presented in Figure 6. Organic carbon was greatest in deep litter site and lowest in the no litter site.

The plots of aggregate stability against soil organic carbon for the deep litter site are given in Figure 7. There was a positive linear relation between aggregate stability and SOC (R^2 = 0.911). The high coefficient of determination indicated that 91.1% of the variation in aggregate stability may be ascribed to SOC. This high correlation between OC and aggregate stability showed that OC acted as a cementing agent linked with stabilizing micro-aggregates into macro-aggregates (Kemper and Rosenau, 1984). This was so because complex interactions exist between SOC storage and aggregate stability (Feller et al., 2001). This was made possible through the formation of stable organo-mineral complexes. Soil organic carbon may have also encapsulated within the stable aggregates, thereby offering protection against microbial processes and enzymatic reaction (Lal et al., 2003; Holeplass et al., 2004). Again, highest mean values of soil carbon were obtained in water stable aggregates 4.75-2.00 mm (16.03 Mg C ha^{-1}) compared with water stable aggregates 1.00-0.50 mm (14.06 Mg C ha^{-1}) and water stable aggregates 2.00-1.00 mm (13.99 Mg C ha^{-1}) in highly weathered soils of Southeastern Nigeria (Onweremadu et al., 2007). However, rapid change occurs in water stable macro aggregates and this could be detrimental to carbon sequestration if soils are exposed (Onweremadu et al., 2010). Humus from which organic carbon is obtained also helped to bind aggregates together which helped to improve how the sizes resisted external disruptive forces. Organic carbon associated with primary particles may have also differed in their chemical compositions with the recalcitrant fraction mostly associated with clay particles (Christensen, 1996). However, this was different for the various aggregate sizes due to increased humification (Laird et al., 2001). Overall, SOC may have improved soil aggregation by forming an organic core surrounded by clay, silt particles and aggregates (Six et al., 2000b). Conversely, in some instances, SOC may be moderately or weakly correlated with aggregate stability (Skøien, 1993; Holeplass et al., 2004).

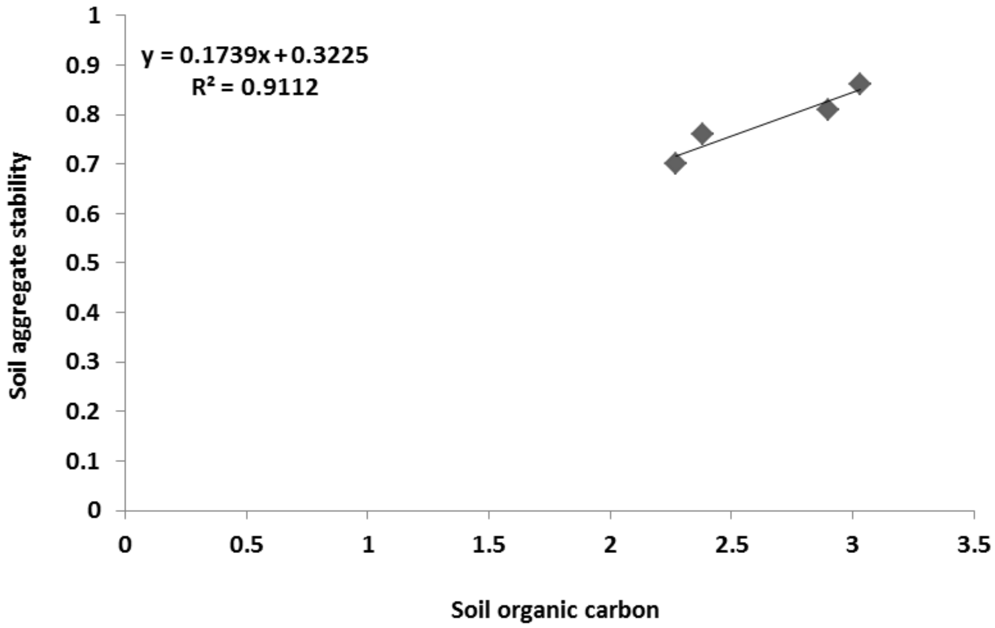

Fig. 7: Regression of aggregate stability on soil organic carbon for deep litter soils

3.4. Carbon sequestration

From this study, it was realised that, under cocoa plantations, soils can help reduce global warming by mitigating the amount of carbon dioxide in the atmosphere by serving as a carbon sinks. This was evidenced by the experimental results which showed the amount of organic carbon content sequestered in the soil with a bulk density of 1557 kg/m^3 and depth of 0.15 m stores about maximum of 30.09 t ha^{-1} of CO_2. Accordingly, Larson et al. (1972) and Cole et al. (1993) have shown that SOC responds linearly to increasing rates of residue or addition of organic inputs in both short and long term experiments. Within the conceptual Soil organic matter model proposed by Six et al. (2000b) which defined a maximum soil carbon storage potential, the soils from the cocoa plantation still have a large saturation deficit and therefore holds great potential for mitigating carbon dioxide emission into the atmosphere. In terms of carbon sequestration potential, the strong linear relationship between SOC sequestered and aggregate sizes suggests that the soils at the cocoa plantation site were low in carbon density (Table 2). Additionally, enhanced C sequestration through C stabilization within the micro-aggregates within the macro-aggregates has been confirmed in afforested and forested soils (Six et al., 2002).

Table 2: Some properties of the soils, soil organic carbon and converted CO_2

Aggregate size (mm)		†SOC (%)	CO_2 (t/ha)	pH (1:2.5)
Deep litter	**0.5 - 1.0**	2.14 (4.99)	18.31	5.60
	1.0 - 2.0	2.26 (5.23)	19.19	5.59
	2.0 - 4.0	2.79 (6.52)	23.92	5.70
	4.0 - 6.0	3.52 (8.20)	30.09	5.77
Shallow litter	**0.5 - 1.0**	2.76 (6.44)	23.63	5.02
	1.0 - 2.0	2.53 (5.70)	20.91	4.88
	2.0 - 4.0	2.58 (6.02)	22.09	4.87
	4.0 - 6.0	2.74 (6.40)	23.48	4.81
No litter	**0.5 - 1.0**	2.27 (5.30)	19.45	5.43
	1.0 – 2.0	2.38 (5.56)	20.40	5.44
	2.0 - 4.0	2.70 (6.30)	23.12	5.48
	4.0 - 6.0	3.03 (7.08)	25.98	5.45

†Values in brackets represent amounts of SOC in Tonnes per hectare.

Bonsu (2007) noted that increasing populations in the tropical region leads to an increasing demand for food and other agricultural products. Also the time allowed for the land to rest for the vegetation to regenerate has decreased. This type of system is non-sustainable and does not permit soil carbon to be sequestered enough. Therefore the cocoa plantation since it is hardly disturbed will have a great potential to store carbon due to its stable state. Further high temperatures in the tropics, for example in Ghana (29.8^{o}C - 37.9^{o}C) promote rapid decomposition of soil organic carbon and the release of carbon dioxide into the atmosphere to compound the problem of global warming. Other limiting factors constraining carbon sequestration include:

(a) Physical degradation due to erosion; (b) Chemical degradation due to nutrient mining and acidification and biological degradation due to loss of organic matter through removal of vegetation in the form of forest clearing and rampant burning of vegetation.

4. CONCLUSIONS AND RECOMMENDATIONS

Soil carbon sequestration differed among soil aggregate size forms and sites. Greater values of total SOC were found in macro aggregates. Again, the results from the study showed that soils from the cocoa plantation had the ability to sequester carbon. This will enhance soil stability and reduce anthropogenic carbon dioxide emission with its attendant negative effects. Significant positive correlation was established between total SOC and aggregate stability at 5% level of probability. It was also confirmed that various aggregate size store different amounts of organic carbon. Also individual soil aggregates bound by humic matter increase the stability of the soil, it was also confirmed that micro-aggregates were bound together by clay and other binding factors to increase the stability of the soil. Aggregate stability and SOC are positively correlated and will enhance root penetration and prevent soil erosion.

Appropriate management of SOM would ensure soil fertility and minimize agricultural impact on the environment through carbon sequestration, erosion control and preservations of soil biodiversity. From the study, it was recommended that to enhance soil carbon sequestration and aggregate stability of soil, close canopy should be encouraged on plantations to enhance increased litter fall and provision of organic input which on decomposition will add more organic carbon to the soil.

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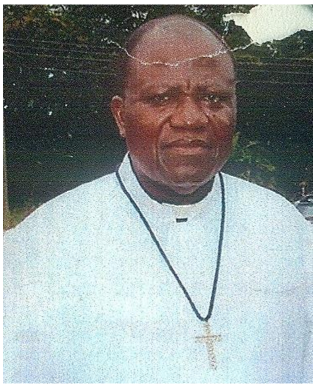

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