EMERGING ISSUES IN SUSTAINABLE FOREST MANAGEMENT: EXPERIENCES AND LESSONS FOR NIGERIA

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Edited by
A. O. Akinwole
V. A. J. Adekunle
O. Y. Ogunsanwo

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DETERMINANT OF CARBON STABILIZATION IN TROPICAL SOILS: A REVIEW OF CARBON SEQUESTRATION POTENTIAL OF SOIL AGGREGATE FRACTIONS

Falade, Oladele Fisayo
Department of Forest Production and Products, University of Ibadan, Nigeria
faladedele@yahoo.com

Abstract
Soils contribute to global climate mitigation through sequestration of carbon. Soils that remain undisturbed for long period of time could be the best choice for carbon sequestration. Quality of organic matter, land management practices and land use types had been considered the major factors influencing accumulation and stabilization of carbon associated with soil aggregate fractions. This understanding had limited the efforts at tracking carbon accumulation and stabilization of various aggregate fractions. However, other factors are becoming relevant in the evaluation carbon stabilization potential of various soil aggregate fraction in different soil texture and types. Therefore these factors require detail description. Organic and inorganic carbon compounds contribute to the soil carbon stabilization and subsequently, enhance carbon sequestration. Understanding of the critical factors that control stabilization of carbon in soil aggregate fractions is limited. This limits the efforts on how to optimize carbon sequestration potential among soil aggregate fractions and soil types and consequently, one of the reasons for unabated evolve of greenhouse gases from soils to the atmosphere. Therefore, brief description of factors that influence and optimize the sequestration of carbon in tropical soils were reviewed. Hence, quantity and quality of organic matter, availability of basic cations; proportion of fine particle fraction in the soil; land management practices option; organic and inorganic carbon concentration and soil moisture content were identified as the major factors influencing the soil carbon stabilization in tropical soils. The processes involve in carbon stabilization of tropical soils could be classified into chemical and physical protecting mechanisms. Organic compounds derive from plant origin enhance soil particle aggregation while cations facilitate organo-mineral formation among soil fine particles. Surface area specificity is essential facilitator of organo-mineral formation among soil fine particles.

Keywords: Tropical soil; Soil aggregate fractions; Carbon sequestration; Soil carbon stabilization.

Introduction
Forest soils are important stable pool for carbon storage and contribute immensely to global climate mitigation because they could remain undisturbed for long period of time. The carbon reservoir could be organic and inorganic carbon (Li et al., 2016) that is adsorbed on soil mineral fractions. Soil organic and inorganic carbon are important carbon reservoir in soils and are necessary for carbon sequestration but quantification of soil inorganic carbon are not adequately emphasized. Most times inorganic carbon

fraction is not considered in the estimation of soil carbon stock because it does not fluctuate frequently in the soil and sometimes, it proportion could be negligible when compare with organic carbon fraction. However, some organic compounds found in the soils contribute to the formation of organic carbon fraction of the soil and also, sometimes inorganic carbon fraction. Organic compounds that inhibit bacterial activity and mineralization in the soil enhance carbon stabilization within micro-aggregates in the soil profile. Also, organic compound contents of the soil can serve as binding agents in the formation of soil aggregates and structure.

Soils contribute to global climate mitigation through stabilization and sequestration of carbon. Quality organic matter, management practices and land use types had been considered as the major factors influencing accumulation and stabilization of carbon associated with soil aggregate fractions. This understanding had limited the efforts at tracking carbon accumulation and stabilization potential of various aggregate fractions. However, other factors are becoming relevant in the evaluation carbon stabilization potential of various soil aggregate fraction in different soil texture and types. Therefore these factors require detail description. Furthermore, the identification of these factors and their roles give an insight into the adsorption mechanisms of carbon on various soil aggregate fractions. These factors can be categorized into chemical and physical processes. Hypotheses of this study include, whether quantity and quality of organic matter, basic cations, proportion of fine particle fraction, management practices, organic and inorganic carbon concentration and soil moisture content contribute significantly to the soil carbon stabilization and sequestration. The objective of the review is to determine factors that influence carbon stabilization in tropical soils with a view to understanding the carbon sequestration potential of tropical soils.

Soils that remain undisturbed for long period of time could be the best choice for carbon sequestration. Hence, forest soils are important stable pool for carbon in the terrestrial ecosystem. The relationship between land use and accumulation of soil carbon are difficult to predict among soil types and texture because of several interactive mechanisms. Also, the relationship between soil carbon and aggregates fractions is complex and not clearly understood because formation of organo-minerals is determined by different mechanisms. Organic and inorganic carbon contribute to the formation of soil carbon stabilization and subsequently, enhance carbon sequestration. However, most times inorganic carbon is not considered as part of carbon stock in many studies because it does not often fluctuate in the soil as the organic carbon. Thus, accurate estimation of soil carbon stock density and sequestration remain incomplete without soil inorganic carbon component.

Several organic compounds are found in the soil and they are from different sources and forms. Although most of the naturally occurring organic compounds in soils are of plant origin. Association of organic compound and clay mineral leads to accumulation of soil carbon and subsequently, aggregation of these fractions leads to formation of micro-aggregates and macro-aggregates. The importance of organic compounds in micro-aggregates and macro-aggregates stability in tropical soils has not been adequately studied and elucidated. Some organic compounds improve while some disperse soil aggregates by different mechanisms. Understanding of the critical factors that control stabilization of carbon in soil aggregate fractions is limited. This limits the efforts on how to optimize carbon sequestration potential among soil aggregate fractions and soil types and consequently, one of the reasons for unregulated release of greenhouse gases from soils to the atmosphere. Therefore, brief description of factors that control and optimize the accumulation of organic compounds in tropical soils were reviewed.

Quantity of organic matter

Many physical, chemical and biological properties of soil surface horizons depend largely on the soil organic matter content (Feller *et al*., 1992). Soil organic matter content ranges from less than 0.2% in desert soils to above 80% in peat soils. In temperate region, soil organic matter ranges from 0.4 to 10.0% while in tropical regions it ranged from 3.0 to 4.0% and those of semi-arid area is 1.0 to 3.0% (Smith *et al*., 2000). Post *et al*. (1990) reported that loss of soil carbon contributes significantly to atmospheric carbon dioxide level. The soil amelioration potentials of greenhouse gases has not been critically emphasized in the developing countries and soils can be a major source of CO_2, CH_4 and N_2O emission to the atmosphere. Conversely, soils can be purposefully managed to serve as effective sink.

The main source of soil organic carbon is plant dry matter and it could be incorporated into soil fraction through decomposition and humification of dry matter. Warm and humid climate with a long wet period which characterise tropical region enhance high net primary productivity through photosynthesis and consequently, it encourages soil organic matter decomposition and sequestration. A large proportion of the annual leaf litter decomposed within a year, usually between 2 to 5 months (Egunjobi and Onweluzo, 1979). Sausen *et al*. (2014) reported that soil carbon accumulation is largely dependent on net primary productivity. Tropical dry forest have 50-75% net primary productivity of humid forest because of the reduction in growth during the dry season (Murphy and Lugo, 1986). Therefore, soils of humid forest present opportunity to conserve or sequester carbon (Lugo and Brown, 1993 and Dixon *et al*., 1994).

Factors that determine the formation of soil organic carbon include the quantity and quality of organic inputs to the soil while the breakdown is determined by the interactive of factors which determine the rate of oxidation and decomposition of the organic molecules (Anderson and Flanagan, 1989).Although tree biomass is stable and large sink for atmospheric carbon, there is uncertainty concerning the influence of their organic matter input on soil carbon stabilization. However, Wiesmeier *et al*. (2009) reported that soil carbon increases under hardwood and decrease under softwoods tree plantation. The quality of organic matter input influence hydrophilic and hydrophobic nature of soil aggregates. Soil hydrophobicity is related to the formation of fulvic acid coatings around soil mineral particles. The dry fulvic acid coatings, which is a metabolic product of soil micro-organisms, repel water and create localized dry spots in soil (Tan, 2005).

Conversely, Oades (1984) reported that dispersion of clay particles from micro-aggregates is enhanced by adsorption of complex organic acids which increase the negative charges on clay minerals. Although, it can be made ineffective by polysaccharides of mucilages produced by fungi, bacteria and plant roots. Also, adsorption of hydrophilic organic compounds by soil particles has received increasing attention but the complexity of the numerous processes involve and their dynamics are still poorly understood. Tan (2005) believed that most of these processes will require ionization and protonation of organic compounds so as to facilitate the adsorption on soil mineral particles. Morley *et al.*, (2005) reported that both water repellant and wettable soil samples contained hydrophobic compounds but water repellant soils contained polar compounds of high relative molecular mass. Fatty acids and esters, plant and cuticular waxes, (Horne and McIntosh, 2000; Morley *et al.*, 2005)plant root exudates were implicated in previous studies, though chemical characterisation of these compounds have yet to be achieved and consequently the molecular basis of water repellency is unclear.

Organic compounds enhance aggregate stabilization and are vital for stable carbon storage and thus has not been emphasized. Organic carbon stabilization involves the protection and preservation of soil carbon in the soil aggregates (Honttoria *et al.*, 2016). Soil organic compounds improve aggregate stability of different fractions by different mechanisms. Soil aggregates are developed from association of soil organic matter and soil mineral particles (Mann *et al.*, 2016). Micro-aggregates and macro-aggregates are distinquished by their size and most times, stabilization of organic carbon takes place within the micro-aggregates.

Previous studies indicated that topsoil determine the soil carbon stabilization (Guo *et al.*, 2016; Yang *et al.*, 2008). However, recent studies indicated that subsoils carbon is also important reservoir for greenhouse gases but the factors controlling their accumulation may be different (Zhao, 2014; Bernal *et al.*, 2016). Soil carbon stabilization is an indicator of wide range of soil properties and also, it can be influenced by many factors. Sometimes there could be soil carbon stratification but no net accumulation in undisturbed soils. It show that there are several factors responsible for rate and site of organic carbon stabilization among the soil particle size fractions.

Quality of organic matter

Despite the role of net primary productivity, some tree species seem to be less effective in biomass accumulation than the other tree species. Consequently, the rate of soil carbon accumulation could be influenced by chemical composition of dry matter of tree species grown on soils. Some fractions of soil organic matter may be labile and others recalcitrant depending on the lignin and volatile content of the organic matter. Therefore, detail understanding on response of soil carbon to change in plantation species is limited. Although several mechanisms have been claimed to be responsible but few studies provide objective evidence for the processes that occur. Therefore, information on the impact of afforestation on properties of soil organic matter required further investigation. Also, despite considerable efforts to understand the effects of afforestation on the dynamics of carbon in the soil, detail understanding of factors influencing its accumulation is yet to be resolved. These have made evaluation of factors that determine carbon distribution and stratification in soil profile difficult especially in weathered soils of Southwestern Nigeria.

Consequently, information on the implication of indigenous trees for afforestation on quality of soil organic matter are scarce because of the lack of long-term investigation (Li *et al.*, 2016). One of the effective methods to improve soil carbon sequestration is the planting of suitable forest tree species, though there is limited knowledge on these choice species (Moghiseh *et al.*, 2013). The planting of choice species can lead to significant change in soil organic carbon. The capacity of indigenous tree species for optimum accumulation of soil carbon have not been fully investigated, although Ayoubi *et al.* (2011) reported higher soil organic carbon for coniferous forest species than those of deciduous tree species.

The distribution of organic carbon among soil aggregates varied among soil types, soil texture and management practices. Young (1976) reported that organic matter content of top soil in the forest may be considered low if it below 3.0% and 2.0% for soils with sandy-clay to clay and sandy-clay-loam to sandy loam, respectively. Organic matter content of soil in a locality fluctuates between relatively narrow limits and influenced by textural characteristic of the soil. Therefore, mechanisms and binding agents that are responsible for carbon stabilization of different soil aggregates and textural characteristics are not the same. Soil organic compounds influence aggregate stabilization of different sizes by different mechanisms. Agboola and Ayodele (1987) considered organic matter ranged between 0.0 and 3.0% as low, 3.4 and 4.8% as medium and above 4.8% organic matter as high for tropical forest soils.

Proportion of Fine Particle in the Soil

There is inconsistent reports on the rate of accumulation of different soil particle sizes. Yang *et al.* (2016) reported that organic carbon storage of silt and clay is significantly greater than sand particles. He claimed that organic carbon storage of a land use type is determined by its proportion of fine particles. This is because soil organic matter of clay is considered to be more sensitive to changes in climate than sand fractions (Li *et al.*, 2015). It is a common assumption that sand-size particles starts to accumulate organic carbon only after the silt and clay particles are exceeded. Other studies shown that clay minerals with rough edges surfaces contribute more to organic carbon storage and therefore, organic carbon accumulation in soil depend partially on specific surface area of soil clay minerals (Mayer and Xing, 2001). Also, studies have shown that accumulation of soil organic carbon storage occurred through interaction with soil mineral surfaces and cations (Sausen *et al.*, 2014; Chevallier *et al.*, 2010). This implies that organic carbon accumulation in soils may be primarily controlled by organic carbon associated with silt and clay particles. Clay and silt have greater surface area than sand fraction. Usually, the adsorption of water, nutrients and attraction for each other are all surface phenomena hence clay has greater adsorptive capacities than silt and sand fractions. Therefore, the finer the texture of a soil, the greater the effective surface area exposed by its particles and the more effective in the accumulation of soil carbon.

Sausen *et al.* (2014) found that the availability of calcium and nitrogen influence carbon storage in soil. The stability of macro-aggregates is also enhanced by multivalent cations which acts as bridges between organic colloids and clay minerals. Therefore, detail understanding of organic carbon accumulation in different soil size fractions require more investigation.

Management Practices

However, other studies have shown that soil organic carbon on silt and clay fractions could be affected by management practices. Also, Jordan *et. al.* (2014) demonstrated that soil organic carbon concentration in the interior layer of the aggregates was higher in mulched soils than conventionally tilted soils. Therefore, management practices can be used to maintain, restore and enhance quantity of carbon stored in forest soils. Park and Smucker (2005) investigated the spatial distributions of carbon and nitrogen mineralization within the macro-aggregates of silt clay loam soil and reported that exteriors of aggregates contained more labile carbon with greater mineralization rates than interiors in conventional and no tillage system. The study also found that total carbon increase approximately 1.6 fold by changing the management system from conventional tillage to no tillage for a period of 36 years.

Organic carbon and water content

Manns *et al.* (2016) observed that correlation between soil organic carbon and aggregate sizes is a reflection of the amount of water that soil aggregates can hold. Therefore, water holding capacity of soil influence soil organic carbon in all soil textural classes. Further studies revealed that accumulation of soil carbon on fine aggregates that remain moistened for most times of the year has high potential for carbon stabilization (Burmann *et al.*, 2007).This suggest that moisture level above water holding capacity of soil would reduce carbon mineralization and enhance carbon stabilization in the soil.

Organic and Inorganic Carbon Concentration in the Soil

Most studies on carbon sequestration have been focused on the surface horizons of soil but inorganic carbon have rarely been considered. The effects of soil particle fraction on accumulation of soil organic carbon, soil inorganic carbon and soil total carbon along soil depths have rarely considered. Raheb *et al.* (2017) study the effect of arid, semi-arid and dry sub-humid climates on soil organic, inorganic ad total carbon and observed a high soil inorganic and low organic carbon contents in the soil of arid region of Northwest of Iran while contrary result was obtained in soils of humid forest.

Conclusion

The different factors involve in carbon stabilization of soil aggregate fractions were elucidated and classified into chemical and physical protecting mechanisms. Chemical protecting mechanisms include cations on organo-mineral complex, organic and inorganic carbon concentration and soil moisture content while physical protecting mechanisms include quantity and quality of organic matter, proportion of fine particle in the soil, land management practices. Factors influencing carbon sequestration involve interactive mechanisms. Therefore, it is difficult to evaluate the effect of a mechanism in stabilization process. Organic compounds derive from plant origin enhance soil particle aggregation while cations interaction enhance organo-mineral formation among soil fine particles. Surface area specificity are essential facilitator of organo-mineral formation among soil fine particles.

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