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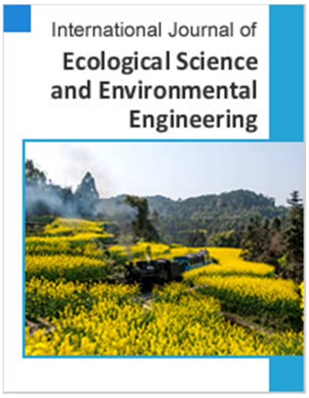

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Carbon Sequestration for Enhanced Soil Quality in the Lake Victoria Crescent of East Africa

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Abstract
Soil carbon sequestration is a natural, cost-effective and environmentally-friendly process and once sequestered, carbon remains in the soil as long as restorative land use, no-till farming and other appropriate management practices are followed. This study aimed at quantifying the carbon sequestered under different land management practices for enhanced soil quality in the Lake Victoria crescent of East Africa. Six land management types were selected (agroforestry, upland natural fallow, mulching, swamp agro-ecosystem, crop rotation and swamp natural fallow). Soil samples under land that was under these management practices for a long period (10 years) were collected and analyzed for organic carbon content to a depth of 60 cm (0-30 and 30-60 cm). Soil pH, bulk density and texture were also analyzed. The relationship between bulk density, soil texture and soil organic carbon content in the soil was also established. This study was carried out at MUARIK (Makerere University Agricultural Research Institute, Kabanyolo) in Wakiso District of Central Uganda. Thirty six (36) soil samples were collected for analysis of the selected parameters. Results show that carbon sequestration is land management practice-dependent ($p < 0.05$); management practices with ground cover throughout the year registered significantly higher organic carbon content of between 136 to139 Kg ha^{-1}, while upland natural fallow registered a low quantity of organic carbon (87 Kg ha^{-1}). In the swamp agroecosystem, it was shown that conversion of swamps to agriculture, with judicious drainage, increased soil organic carbon content by 15 to 20%. Increasing biomass inputs to the soil increased the carbon sequestered. It was concluded that adoption of soil and water conservation practices greatly reduces loss of soil organic carbon, especially under agroforestry systems. Therefore, promotion and adoption of agroforestry as a key land utilization type can significantly contribute to carbon sequestration and improved physical, chemical and biological soil properties. This may lead to sustainable crop productivity in tropical farming systems.

1. Introduction

Carbon dioxide from the atmosphere can be sequestered or stored as soil organic carbon to improve soil quality, agricultural productivity and overall quality of human, plant and livestock life. There is growing concern that increased carbon dioxide concentration in the atmosphere results in global warming and climate change, with disastrous consequences on the environment. However, the concentration of this greenhouse gas can be significantly reduced through appropriate agricultural practices that provide an important avenue for storing carbon in soil [1]. Increasing the level of Soil Organic Carbon (SOC) has long been known to improve soil quality and agricultural productivity. Soils with high levels of organic matter exhibit improved nutrient release, water retention and resistance to erosion [2, 3]. Judicious use of fertilizers and organic manures maintains SOC content at a high level than in low external inputs systems. It has been confirmed that organic carbon is responsible for crop yield variation by 60% [4]. Forest and agricultural soils, the biggest CO_2 sinks, are estimated to contribute a net removal of about 2gtCy^{-1} from the atmosphere through input processes such as photosynthesis and accumulation of soil organic matter. The projected potential to increase this net removal of carbon from the atmosphere through adoption of improved land and soil management strategies is 5-10gtCy^{-1} [5].

Cultivated soils provide the world with food and fiber that have been, and continue to be, essential for human survival and economic growth. Thus, protection and enhancement of the soil resource base through carbon sequestration encourages sustainable economic development and food security [6]. Carbon sequestering practices can substantially reduce economic costs to farmers and government and fuel and fertilizer use per unit of food grown; in the long run, this leads to lower agricultural production costs and consequently, fewer resources are allocated to solving environmental problems such as land degradation, climate change and water pollution [7].

Declining soil fertility is one of the major factors limiting crop and animal production in Uganda. Most of the soils are being used for agriculture, especially those in wetlands and other fragile ecosystems. Natural forests are also being cleared and this has led to increased levels of carbon dioxide in the atmosphere at the global scale [8]. This increase in atmospheric CO_2 has resulted into increased temperatures and changing weather patterns that have had profound impacts on human societies and the natural environment [9]. Stepwise re-accumulation of farming systems carbon involving tree planting and soil conservation in East Africa has the potential to increase carbon stocks from 70 to 130 tCha^{-1} and to increase crop yields by about 40% [10]. No study has so far been carried out in the East African region to quantify soil organic carbon sequestered under different land management systems in a bid to enhance soil quality for agricultural production purposes.

The general objective of this study was to assess soil quality by quantifying the carbon sequestered in soils under different land management practices in the Lake Victoria crescent of East Africa. The specific objectives of the study were: (1) To find out the amount of soil organic carbon in the different land management practices; and (2) To evaluate some selected soil chemical and physical characteristics that are enhanced by the presence of soil organic carbon.

2. Materials and Methods

2.1. Description of the Study Area

The study was carried out on selected land management practices that are commonly employed by most farmers in Uganda at Makerere University Agricultural Research Institute, Kabanyolo (MUARIK), in the Lake Victoria crescent of East Africa. The institute is located 17 kilometers north of Kampala (the capital city of Uganda) (0028'N, 32037'E) and at an altitude of 1250m-1320m above sea level. The study was carried out between January 2005 and January 2015. The climate of MUARIK is classified as moist tropical. The rainfall pattern is bimodal, with an annual average of 1160mm, with the first rains from March to May, while the second rains are from September to November. The mean annual maximum temperature is about 25.9°C. The soils are formed on colluvium from quartzite, gneiss and other basement complex rocks; on the hill slopes, colluvium enriched soils with lateritic gravel are common (Kandiudalfic eutrodox) [11].

2.2. Soil Sampling and Analysis

Soil samples were collected from the sites which included (i) Upland natural fallow that contained shrubs and grasses such as elephant grass, couch grass and spear grass, among others; (ii) Swamp agro-ecosystem (carrots, maize, yams and sugarcane); (iii) Swamp natural fallow that contained plants such as *Calliandra*, *Phragmites* spp (reeds), papyrus, *Commelina bengalensis* and other swamp natural weeds; (iv) Crop rotation in which maize, beans and sweet potatoes were rotated; (v) Agroforestry contained *Acacia* trees, coffee, pawpaw, mangoes, jackfruit and avocado trees intercropped with cassava and beans; and (vi) Mulching (banana plantation) using crop residues (banana leaves and pseudo stems). These are the most dominant land management interventions for carbon sequestration and climate change mitigation in tropical farming systems as observed by Basamba et al. [7]. Soil samples were collected from the 0-30 and 30-60cm depths. Three core samples were taken from each layer and site for determination of bulk density and other soil parameters. A total of 36 samples were collected from the profile pits and the augerings. They were kept in plastic bags for subsequent processing. Analysis of the soil samples for texture, bulk density and pH was done as described by Okalebo *et al.* [12] and SOC was determined using the wet dichromate oxidation method [13]. SOC (t/ha) was determined using the formula "Soil C (Kg ha^{-1}) = C (kgkg^{-1})* bulk density (kgl^{-1}) * depth (cm)" [14].

Data was assembled within Excel spread sheets and later analyzed using summary statistics and analysis of variance procedure (ANOVA) in the Genstat program [15]. For statistical analysis of organic carbon variation down the soil profile, the student t-test was used [16].

3. Results and Discussion

3.1. Soil Organic Carbon in the Different Land Management Practices

Long term studies on soil management have demonstrated that soil conservation practices not only reduce soil erosion but also increase soil organic matter. In line with this observation, Sanchez [17] has confirmed that the organic carbon content of a soil in equilibrium with the vegetation is a function of annual addition and decomposition of organic carbon. In this study, it was shown that the conversion of swamps into agricultural fields resulted into increased SOC of approximately 15% in the plough able layer (Table 1). However, down the soil profile, the carbon stocks decreased (Table 2) because draining swamps releases CO_2 to the atmosphere, which is difficult to restore to the original SOC level in a human life span [8, 18]. Decomposition of residues is extremely slow under anaerobic conditions; this scenario was observed in the soils of the swamp natural fallow which form under water logged conditions. The presence of slowly decomposing organic residues can significantly contribute to the stored carbon pools in the soil [18].

Table 1. *Soil properties in relation to Organic Carbon in top soil (0-30cm) in the different land management practices.*

				Texture			
Site (0-30cm)	C (kgha^{-1})'000	pH	Bulk Density (kg l^{-1})	Sand (%)	Clay (%)	Silt (%)	Textural Class
Agroforestry	72.03d	5.9a	1.14cd	38de	49a	13bc	Clay loam
Upland Natural Fallow	86.79c	5.8ab	1.273a	53bc	37b	10d	Sandy clay loam
Mulching	139.20a	5.8ab	1.221b	61a	29cd	10d	Sandy clay loam
Swamp Agroecosystem	135.88a	4.5e	1.06d	53bc	27d	20a	Sandy loam
Crop Rotation	84.03c	5.1c	1.16c	42d	48a	10d	Sandy clay loam
Swamp Natural Fallow	117.68b	4.9d	0.99e	55b	31c	14b	Sandy loam
Grand mean	105.94	5.33	1.14	50.33	36.83	12.83	
SEM	28.8	0.58	0.10	8.62	9.64	3.92	
LSD (α =0.05)	8.0	1.13	0.48	4.36	4.61	2.94	

In the same column, means followed by the same letter are not statistically significantly different by F-protected LSD at α = 0.05.

Table 2. *Soil properties in relation to Organic Carbon in sub soil (30-60cm) in the different land management practices.*

				Texture			
Site (30-60cm)	C (kgha^{-1})'000	pH	Bulk Density (kg l^{-1})	Sand (%)	Clay (%)	Silt (%)	Textural Class
Agroforestry	46.4c	6.4a	1.40a	25f	67a	8ab	Clay
Upland Natural Fallow	63.9a	5.3c	1.42a	34d	55b	11a	Clay
Mulching	41.3d	4.4d	1.40a	38c	56d	6b	Clay
Swamp Agroecosystem	53.7b	5.2c	0.34c	64a	23d	13a	Sandy Loam
Crop Rotation	35.2e	5.9b	1.15b	30e	64a	6b	Clay
Swamp Natural Fallow	62.1a	4.5d	0.18d	56b	34c	10a	Sandy Clay Loam
Grand mean	50.4	5.28	0.98	41.17	49.83	9.00	
SEM	11.5	0.78	0.57	16.02	17.84	2.83	
LSD (α =0.05)	5.0	1.31	1.12	5.94	6.27	2.50	

In the same column, means followed by the same letter are not statistically significantly different by F-protected LSD at α = 0.05.

Soil Organic Carbon (SOC) content in the top soil was generally highest in mulching (banana field) and swamp agro-ecosystems. The swamp agro-ecosystem registered a notable rise in SOC of approximately 15-20%, thus proving more efficient in sequestration of carbon than swamp natural fallow. Upland natural fallow and crop rotation registered similar carbon contents of 86.79 and 84.03 tha^{-1}, respectively. The lowest SOC content of 72.03tha^{-1} was measured under the agroforestry land management practice.

The highest carbon content of 63.9 Kg ha^{-1} was registered under upland natural fallow and the lowest SOC content under crop rotation practices (Table 2). A notable decline in SOC content was observed in the swamp agro-ecosystem as compared to the natural fallow practice. Organic carbon decreased by 40-50% from the top to the bottom of the soil profile in all the land management practices.

Mulching practice registered the highest SOC, which can be attributed to the surface soil conditions. This confirms the fact that carbon exists as an inseparable component of vegetation, litter and soil organic matter [14, 19]. It is important to note that soil organic matter content increases through carbon sequestration and has a positive influence on soil quality and fertility. Low soil organic matter indicates low levels of nutrients [20]. Small quantities SOC were sequestered under agroforestry management practice due to the influence of the long growing period of tree crops, the amount of litter that was produced by the trees and the canopy coverage; all these were low levels in the sampling sites. However, there was no drastic decrease in carbon content down the soil profiles due to the extensive rooting systems of tree crops to the deeper soil layers [21].

The narrow ranges of SOC in crop rotation sites may be due to the rapid mineralization of organic residues due to increased aeration as a result of frequent tillage, high soil temperatures that lead to higher decomposition rates, lower litter inputs and the shorter duration of organic residue application in this land management type [7, 9].

Organic carbon decreased by more than 40-50% from the top to bottom of the soil profiles in all the land management practices (Table 2). This may be explained by the lower biomass observed in all the management practices in the subsoil layers. The high SOC content in the natural fallow could be attributed to the high carbon content in Leucaena, Calliandra and other biomass due to their low polyphenol and lignin contents that make them decompose faster [22].

It should be noted that soil textural differences are more related to parent material than land use [23]. The dominant soil textural classes in the study area were sandy clay loam, clay loam and sandy loam (Tables 1 and 2). The capacity of the soil to sequester carbon is greatly influenced by soil texture [12]. However, some soil physical properties deteriorate with cultivation (Tables 1 and 2). This may render the soil more susceptible to runoff and erosion losses and eventual decrease in organic carbon [17]. This was observed in all upland management practices which registered a significant decrease in organic carbon content. Coarse particle concentration in the sub soil was observed in the upland ecosystems. This may have adverse effects on the root growth of arable and tree crops [24].

Bulk density influences both the capacity and intensity of nutrient uptake [25] and was shown by good vegetative growth indicators, especially under the swamp ecosystems. It is also believed to be positively influenced by soil organic carbon content [17].

3.2. Selected Soil Characteristics Enhanced by Soil Organic Carbon

3.2.1. Soil pH

The Agroforestry land management practices were less acidic, with a pH of 5.9. More acidic conditions were registered under the swamp agro-ecosystem followed by swamp natural fallow and finally crop rotation, all of which were of moderate acid pH (Table 1). More acidic conditions were registered under swamp natural fallow and mulching management practices, with pH values of 4.4 and 4.5, respectively. The pH values from agroforestry soil samples were slightly acidic to neutral (Table 2). Soil organic matter has the potential to buffer pH so as to maintain favorable conditions for crop growth [25].

3.2.2. Soil Bulk Density

Upland natural fallow had the highest bulk density of 1.27 kgl^{-1}, followed by mulching, with a bulk density of 1.22 kgl^{-1}. The lowest bulk density was registered under swamp natural fallow. Upland natural fallow registered the highest bulk density of 1.42 kgl^{-1}. The lowest bulk density was under swamp natural fallow at 0.18 kgl^{-1}. This was followed by the swamp agroecosystem and crop rotation with bulk densities of 0.34 and 1.15 kgl^{-1}, respectively. Soil bulk density is significantly positively enhanced by presence of organic carbon as observed by Zhao et al. [18] and Zehetner et al. [19].

3.2.3. Soil Texture

Upland natural fallow, mulching and crop rotation had the same textural class (sandy clay loam) (Table 1). The swamp ecosystem had the same textural class as agroforestry (sandy loam). The swamp agro-ecosystem had a sandy loam texture, whereas the swamp natural fallow had a sandy clay loam texture. The rest of the land management practices had a clay texture (Table 2).

4. Conclusions

Carbon sequestration in an agricultural context is subordinate to the farmers' requirements for food and fiber production, labor and financial resources to maintain sufficient land cover to minimize the adverse impact of land and environmental degradation. This calls for adoption of agroforestry by tropical smallholder farmers as the best land management option under a climate change environment as indicated by Basamba et al. [26] and Basamba et al. [7]. There was a general decrease in organic carbon down the soil profile. Therefore, for increased potential of soils to sequester carbon, there is need to adopt plants with extensive deeper rooting systems, hence adoption of agroforestry is inevitable, particularly in Uganda where there is a high potential of fruit trees such as Mangoes, Citrus and coffee. In addition, the depletion of fuel wood from the wild presents a great need for adoption and engagement of the general population in agroforestry, with an urgent need for the provision of advisory and technological input services.

Increasing carbon sequestration in soils involves increasing the quantity of organic matter returned or added to the soil or reducing the SOC lost by oxidation or erosion or a combination of both; this can be achieved by various soil conservation practices.

A common soil management practice aimed at optimizing the soil physical environment for plant growth is to incorporate crop residues. These may lead to increased soil organic carbon, moisture storage, rooting depth and nutrient status and reduced bulk density, soil temperature, soil compaction, runoff and soil erosion. Soil organic carbon losses can be reduced by several tillage operations such as zero tillage, reduced tillage, stubble mulching and conventional plowing [27].

Improvement in the levels of SOC is possible if soil productivity increases, especially through higher fertilizer application rates and intensive cropping systems which increase biomass production. Maintenance of wetlands in their natural state is a good policy for enhancing carbon sequestration. However, judicious management of wetlands by maintaining wetness ensures sustainable organic carbon content in wetland soils. Ecologically compatible land use systems such as cultivation of perennials should be adopted. Annual crops, especially paddy rice and yams, are a major source of livelihoods for wetland farming communities from this region.

Crop rotation should include perennial forage crops for hay or pasture so as to ensure increased biomass production and continuous soil cover throughout the year, thereby improving soil quality and carbon sequestration.

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