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Impact of organic manuring on soil carbon sequestration under monoculture and perennial systems in tropical rainforest of Nigeria

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Organic carbon is a vital indicator of soil health, which can contribute to a sustainable agroecosystem. In Africa, mismanagement of agricultural soils has depleted the organic carbon pool. The decline in soil organic carbon has important implications for food security and environmental sustainability. This study examined the impact of monoculture and perennial systems on soil carbon sequestration after fifteen years of cropping in a tropical rainforest of Nigeria. Agronomic management in the monocultures of maize and cassava included farmyard manuring, mineral fertilizers, and tillage practices, while the leaf litters from the avocado and plantain trees remained as soil mulch in the perennial systems. A total of 640 soil samples obtained in the first 15 cm depth from the monoculture and perennial systems were analyzed for particle size distribution, bulk density, and soil organic carbon. Results indicated that clay particles in soil increased significantly ($P \leq 0.05$) in the perennial systems than those of monocultures, whereas the bulk density decreased significantly ($P \leq 0.05$) under perennial systems (averaged 1.31 Mg m^{-3}) compared to monocultures (averaged 1.60 Mg m^{-3}). The soil carbon content (averaged 1.47 %) and carbon stock (28.77 Mg C ha^{-1}) of the perennials was significantly higher ($P \leq 0.05$) than those in the monocultures (averaged 0.87 % and 20.86 Mg C ha^{-1}, respectively). We conclude that permanent soil mulching with plant litters under perennial systems can increase carbon sequestration. The seasonal cropping and tillage under the monoculture system can decrease the soil carbon stock. Organic mulching is a regenerative practice that can restore the carbon pool while improving soil health and crop productivity in agroecosystems across Africa.

1. Introduction

Soil carbon sequestration through croplands has stimulated global interest in the last three decades (Minasny et al., 2017). Soil carbon sequestration is one of the mechanisms where carbon storage is enhanced, thereby reducing the rate of atmospheric CO_2 concentration (Dignac et al., 2017). Soil is a large pool of highly active humus containing twice as much carbon as vegetation and atmosphere pools (Wang et al., 2017), and thus, cropland soils are important sinks for carbon storage (Poeplau & Don, 2015). However, agricultural systems across Africa contribute to the carbon footprint in soil and the atmosphere, increasing CO_2 production. Poor soil and crop management practices such as continuous tillage, monocultures, and removal of organic residues increase CO_2 emissions (Bationo & Buerkert, 2011). Regenerative agricultural practices such as permanent soil covering with organic residues or cover crops, minimum or conservative tillage, and crop diversification can contribute to soil carbon sequestration and mitigation of CO_2 emissions (Oyeogbe et al., 2017).

The amount of carbon sequestered in the soil is a function of the long-term input of organic materials such as leaf litters, plant and harvest residues, and animal manures (Poeplau & Don, 2015). For example, organic residues from plants and animals under mixed farming systems in West Africa increased the soil organic carbon content (Bationo & Buerkert, 2011). Also, a long-term soil fertility experiment in Nigeria demonstrated that the combination of organic manures and mineral fertilizers was more effective in increasing the soil organic carbon than mineral fertilization alone (Raji & Ogunwole, 2006). Moreover, soil carbon concentration can be affected by the processes of decomposition and erosion (Poeplau & Don, 2015). In tropical Africa, the prevailing high temperature and rainfall also increase the rate of soil carbon decomposition and erosion loss (Igwe et al., 2000).

Restoring the carbon in the soil is not only about mitigating climate change but also enhancing agroecosystem services such as improving air and water quality, reducing soil disturbance and erosion, and ensuring food security. Increased soil organic carbon is a significant indicator of agroecosystem sustainability and is a climate-resilient strategy for alleviating the hidden hunger affecting billions of people while protecting the environment (Rosenberg & Izaurralde 2001). Lal et al. (2006) reported that the accumulation of one-ton carbon in soil per hectare in a year would increase food production to the tune of 30-50 metric tons per year, particularly in Africa.

Thus, the relevance of carbon sequestration in cropland soils is crucial for enhanced soil fertility and crop productivity. However, studies on soil carbon sequestration in diversified cropland systems across Africa are scarce. Our study focuses on soil carbon sequestration in the monocultures and perennial systems under different management practices in the tropical rainforest of Nigeria. We hypothesized that the soil carbon sequestered in the perennials of avocado and plantain would be greater than animal manures and mineral fertilizers in the monocultures of maize and cassava due to the regeneration of carbon material via leaf litter mulching.

2. Material and Methods

2.1. Description of the experimental site and cropping history

The location of the experimental site is in Sapele, Niger Delta of Nigeria, 5o 51’ N, 5o 44’ E; 10 m above sea level. The average temperature and rainfall conditions in the period (2018) under investigation were 26.6 º C and 2406 mm, respectively. The pH of the soil ranges between 5.6- 6.2. And is classified as Ultisols according to the USDA soil taxonomy. The cropping history of the field includes monoculture systems of maize and cassava and perennial systems of plantain and avocado orchard. Both cropping systems have been under cultivation for the past fifteen years. Agronomic management practices in the monocultures included the application of farmyard manure, mineral fertilizers, and conventional tillage, whereas, in the perennials, mineral fertilizers were applied only in the first three years of crop establishment, and the leaf falls from avocado and plantain remained as permanent soil mulch.

The cropping area under investigation of monocultures (maize and cassava) and perennials (avocado and plantain) was 6400 m^2, delineated into four blocks of the experimental unit. Each block (20 × 20 m^2) of the experimental units was treated as a cropping system of maize, cassava, avocado, and plantain and replicated four times. Thus, the experiment design was a 4 × 4 treatment combination under randomized complete block design.

2.2. Soil analyses

From each block of 400 m^2 cultivated area, soils were obtained in every 10 m^2 from the 0-15 cm depth. Thus, a total of 640 soil samples was obtained, made of 40 each from the maize, cassava, avocado, and plantain systems. The soil samples were air-dried and sieved with a 2 mm sieve for particle size distribution and a 0.5 mm sieve for organic carbon analyses. The soil particle size distribution was measured with a hydrometer (Bouyoucos 1936) and organic carbon by the wet oxidation method (Walkley & Black, 1934). Also, undisturbed soil was obtained in quadruplicate for bulk density determination (Blake & Hartge, 1986). The soil organic matter content was derived using the van Bemmelen conversion factor of 1.724 (organic carbon

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content in % multiplied by 1.724), and carbon stocks in soil (Mg C ha^{-1}) in a fixed depth of 0-15 cm was estimated using the following equation 1, from Oyeogbe et al., (2018).

SOC stock =

$$\frac{SOCconc(\%) \times bd\left(Mg\ m^{-3}\right) \times soil\ depth\ (m) \times 10^{4}\ m^{2}\ ha^{-1}}{100} \quad (1)$$

Where SOC is soil organic carbon stock in Mg C ha^{-1}; SOCconc is soil organic carbon concentration; bd is bulk density of soil; m is metres of the soil depth thickness.

2.3. Statistical Analysis

The data collected were subjected to analysis of variance (ANOVA) for the randomised complete block design using the SAS package 9.1 where treatment effects were significant at $P \leq 0.05$, the least significant difference (LSD) test was used to compare the means of each treatment combination.

3. Results

3.1. Particle Size Distribution

The distribution of sand, silt, and clay particles differed among the monocultures and perennials (Table 1). Clay particles increased significantly ($P \leq 0.05$) in the perennial systems (avocado and plantain) compared to the monocultures (maize and cassava), while sand and silt particles remained the same.

3.2. Bulk density

The bulk density was significantly different ($P \leq 0.05$) among the monoculture and perennial systems (Table 2). Soil bulk density decreased in the perennials of avocado (1.29 Mg m^{-3}) and plantain (1.33 Mg m^{-3}) compared to the monocultures of maize (1.59 Mg m^{-3}) and cassava (1.61 Mg m^{-3}).

Table 1. Particle size distribution

Cropland systems		Sand	Silt	Clay
		%		
Monoculture	Maize	95.72±0.26a	1.78±0.17a	2.50±0.25b
	Cassava	96.28±0.28a	1.71±0.20a	2.01±0.28b
Perennial	Avocado	92.53±0.24a	2.25±0.18a	5.22±0.17a
	Plantain	92.88±0.25a	2.48±0.16a	4.64±0.16a
P-value (0.05)		4.21	1.54	1.98

Different letters in the same column mean significant differences. ±=standard deviation, n=40.

Table 2. Soil bulk density and organic carbon content

Cropland systems		Bulk density (Mg m^{-3})	Organic carbon (%)
Monoculture	Maize	1.59±0.09b	0.89±0.19b
	Cassava	1.61±0.07b	0.85±0.18b
Perennial	Avocado	1.29±0.03a	1.53±0.12a
	Plantain	1.33±0.04a	1.40±0.13a
P-value (0.05)		0.21	0.38

Different letters in the same column mean significant differences. ±=standard deviation, n=40.

3.3. Soil organic carbon content and stocks

The soil organic carbon content and stocks (Table 2, Fig. 2) were significantly different (*P* ≤ 0.05) among the monoculture and perennial systems. Organic carbon in soil and the associated carbon stock increased under the perennial cropping of avocado (1.53 % and 29.7 mg C ha^{-1}, respectively) and plantain (1.40 % and 27.9 mg C ha^{-1}, respectively) compared to monocultures under maize (0.89 % and 21.2 mg C ha^{-1}, respectively) and cassava (0.85 % and 20.5 mg C ha^{-1}, respectively).

4. Discussion

4.1. Particle Size Distribution

An increase in the clay content under the perennial systems than those of monocultures could be related to the leaf litters, which contributed to organic matter decomposition and carbon turnover in soil. Sinoga et al. (2012) and Rodriguez-Lado (2017) showed that leaf litter decomposition regulates the clay content and carbon storage in soil. The clay fraction in the soil is generally highly associated with organic carbon storage (Matus et al., 2016). Sausen et al. (2014) reported that high clay particles increased the soil carbon storage in highly weathered soil in Brazil. In the soils under study, the permanent mulching with leaf litters in perennials may reduce raindrop and erosion impact on the clay fractions and organic carbon loss; whereas, seasonal tillage in the monoculture systems exposed the clay fractions and organic carbon to erosion loss. Furthermore, the high concentration of sand and clay fractions than silt could be due to the soil formation process, caused by the underlying sand particles and the clay sequence of the parent rock material (Akpokodje, 1989).

4.2. Bulk density

The decrease in soil bulk density in the perennials of avocado and plantain is closely related to the organic carbon inputs from the leaf litter decomposition. The permanent soil mulching with leaf litters in the perennials of avocado and plantain can contribute to soil carbon storage while reducing carbon loss from the damaging effects of high temperature (Buchkowski et al., 2019). A decrease in the soil bulk density is associated with high organic carbon and stable structural aggregates (Arunrat et al., 2020). The soil bulk density indicates structural stability, which depends on the organic carbon constituents. The structural stability of soil to form and retain stable aggregates is dependent on the binding force of organic matter stabilization (Paul, 2016). Leaf litter decomposition can reinforce the structural aggregates and associated organic carbon storage in soil (Sausen et al., 2014; Capellesso et

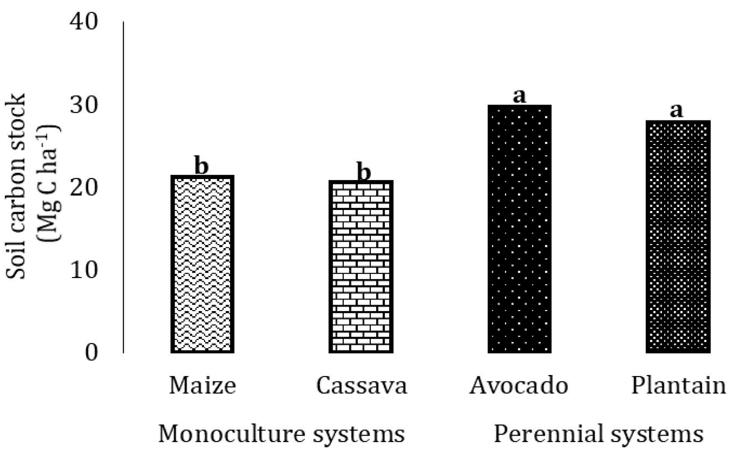

Figure 1. Soil carbon stocks under monoculture and perennial systems. Different letters represent significant difference at *P* ≤ 0.05

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al., 2016), while monocultures disintegrate soil aggregates (Zhou et al., 2020). Increased soil bulk density in the monocultures of maize and cassava may be due to continuous tillage, which may have exposed the organic carbon to rapid decomposition and loss. Don et al. (2011) reported that soil tillage contributes to carbon loss of up to 30-40% compared to semi-natural vegetation such as the perennial system. Increased soil bulk density by the seasonal tillage in monocultures affects the accumulation of organic carbon responsible for forming stable soil aggregates (Zhou et al., 2020).

4.3. Soil organic carbon content and stocks

Increased soil carbon stock in the perennial systems is due to the accumulated organic matter from leaf litters decomposition in the last 10-15 years. Litter contribution to soil organic carbon increased up to 40% compared to soils without litter addition after 120 years of abandonment (Novara et al., 2015). Leaf fall and litter decomposition can reinforce carbon cycling and turnover in soil (Sausen et al., 2014; Capellesso et al., 2016). On the contrary, seasonal tillage in the monocultures decreased the soil carbon stock and associated carbon sequestration. Haddaway et al. (2017) reported that conventional tillage reduces the capacity of soil to sequester organic carbon by exposing the soil surface to erosion and high-temperature effects. More importantly, organic carbon stabilization in cropland soils can positively affect biomass productivity and environmental sustainability. In this study, the perennials of avocado and plantain increase the stability of soil carbon from the uninterrupted conversion of organic residues into humus and the associated sequestration of carbon.

5. Conclusions

Monocultures and perennials are diversified agroecosystems in Nigeria. The sustainability of these cropland systems depends on the soil ecosystem services, particularly the soil organic carbon content. Restoring the soil carbon pool through organic mulching can improve soil health and crop productivity while mitigating the adverse effects of climate change. Permanent soil mulching via leaf litter in the perennials of avocado and plantain contributed to the efficiency of soil carbon sequestration, while seasonal tillage in the monocultures of maize and cassava decreased the carbon sequestration potential. Soils under diversified agroecosystems have the potential to minimize atmospheric CO_2 emissions through carbon sequestration.

Conflict of interest

The authors declare no conflict of interest. Besides, the funders had no role in the study's design, in the collection, analyses, or interpretation of data, in the manuscript's writing, and in the decision to publish the results.

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