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Soil fertility evaluation and land-use effects on soil properties, carbon and nitrogen sequestration in the rainforest of Nigeria

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Abstract

This study investigates changes in soil properties, specifically soil organic carbon (SOC) and total nitrogen (TN), associated with different land use systems derived from forests in the rainforest zone of Nigeria. The land use systems examined include mature oil palm plantation (OP), bush fallow or secondary forest (BF), alley cropping with multi-purpose trees (AC), and continuous cassava cropping with and without fertilizer (FC and UC). Converting forests to cultivated land led to a decrease in SOC and TN content and storage across all soil depths (0-10 cm, 10-20 cm, and 20-40 cm). In the top 0-10 cm depth, the average decrease in SOC and TN storage was 63% and 62%, respectively, while for 0-40 cm, the decrease was 48% and 46%, respectively, for all land use systems derived from forests. Furthermore, the study reveals that even after 5, 10, and 30 years of secondary forest regrowth (BF), alley cropping (AC), and oil palm plantation (OP), respectively, the fertility levels were not restored to those observed in the primary forest. These findings underscore the capacity of forest soils to conserve and enhance soil SOM (soil organic matter), which in turn plays an essential role in SOC sequestration, TN storage, and soil nutrient conservation.

Keywords: Carbon sequestration, land uses, nitrogen sequestration, soil fertility, vegetation.

Introduction

Primary forests and forest derived land uses play vital roles in global carbon cycles and nutrients dynamics in terrestrial ecosystems (Sharma and Rai, 2007; Don et al., 2007; Nair et al., 2009), particularly in the tropics, where forest vegetations are converted to agricultural and other land uses have been on the increase over the past few decades (Fernandes et al., 1997; Lal, 2005). Clearing primary forest for agriculture leads to unsustainable land use with resultant effect on the decline in soil fertility, soil quality and the overall alteration in the global biogeochemical cycles (McGrath et al., 2001; Schrot et al., 2002; Sharrow and Ismail, 2004; Celik, 2005; Sharma and Rai, 2007). Forest conversion into cultivated land affects soil fertility due to its effect on SOM content, which influences ecosystem cycles of nitrogen, carbon, as well as on soil physical properties (Kong et al., 2006; Jelinski and Kucharik, 2009; Nair et al., 2009). Loss of SOC stock when converted from forest to arable land has been documented in several works (Carter et al., 1998). Murty et al., (2002) reported the decline in SOC stock in crop land soils as 16%. It has been shown that about 42% SOC is lost in soil when forest land is turned to crop land and about 59% SOC is lost in soil when grassland is turned to crop land (Guo and Gifford, 2002). For a Mollisol in central Ohio, Puget and Lal (2005) reported that cultivated farm lands had 51+ 4 (equivalent mass) Mg ha^{-1} lesser SOC and lesser 3.5 + 0.3 (equivalent mass) Mg ha $^{-1}$ N within 30 cm soil layer of soil than under forested land. Research findings on the effects of conversion of forest into

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agricultural land and other soil properties like bulk density, total porosity and C:N ratio etc. have been contradictory. For example, while Bayer et al. (2000), Puget and Lal (2005) and Celik (2005) reported significant change in soil bulk density between forest and cultivated sites, Brown and Lugo (1990) found no change in bulk density after forest conversion in Puerto Rico and US Virgin Islands. However, majority of the studies showed that soils under forest had lower bulk density than nearby soils under cultivation. Franzluebbers et al. (2000) and Puget and Lal (2005) reported that forest soils had higher C:N ratio than cultivated soils and the C:N ratio showed the different amount of organic residues in the organic matter pool as a result of contrasting vegetation covers. On the other hand, Jelinski and Kucharik (2009) reported that SOC/TN ratios for 25-cm sampling depth did not differ between the land use systems. Similarly, It has been reported by Geissen et al. (2009) that there was no significant change in the C:N ratio of soils under current land system and also the C:N ratio of soils from 1988 – 2003 were not influenced by land use systems for a wide range of soil groups (Cambisols, Gleysols, Leptosols, Luvisols, Regosols and Vertisols).

The study of the effect of conversion of natural ecosystems e.g. forest to agriculture on soil properties and SOC sequestration has continued to remain a major global issue, especially in recent times because of our collective concern of environmental degradation and climate change. With the renewed emphasis on deforestation and its effect on CO_2 and other greenhouse gases (GHGs) emissions into the atmosphere, there is a need to intensify scientific research in this area, especially in the different ecological zones of the tropics, where such information are limited. Such information is lacking in the rainforest zone of Nigeria and need to be generated from research. This work therefore was undertaken to assess the effects of natural forest and forest derived land uses on changes in soil physico-chemical properties, SOC sequestration and TN storage in an ultisol in the rainforest area of Nigeria. The aim of the study is to investigate specific objectives related to soil properties and nutrient dynamics under different land use systems. The study seeks to determine changes in key soil parameters, including bulk density, porosity, pH, exchangeable bases and acidity, CEC (cation exchange capacity), base saturation and aluminium (AI) saturation in the topsoil. Additionally, the study aims to assess the depth distribution (0 – 40 cm) of soil organic carbon (SOC) and total nitrogen (TN) content, storage, and the carbon-to-nitrogen (C:N) ratio.

The inclusion of TN data alongside SOC data is important due to recent studies highlighting the influence of soil nitrogen dynamics on the sequestration of SOC. It is therefore recommended that investigations into SOC changes incorporate TN data, as suggested by previous research conducted by Kucharik (2007) and Jelinski and Kucharik (2009). In summary, this study aims to provide valuable insights on soil properties, nutrient dynamics, and carbon sequestration resulting from effects of land utilization types. Specifically, it aims to elucidate the inter-relationship between nitrogen and OC (organic carbon) in the soil under varying land uses.

Material and Methods

Description of the Location Site

We collected soil samples from Umudike Abia State (50 25^1 N and 70 35^1 and 125 m elevation) in south-eastern Nigeria. The study area lies within the humid tropical environment, supporting lowland rainforest vegetation and is known by two distinctive seasons, namely, the raining months (April - October) and the dry months (November - March). Annual rainfall average is 1800 and 2200 mm with a bimodal pattern (early April to end of July and middle of August to the end of October). The monthly mean rainfall of the area is optimum between 250 – 300 mm and is recorded in September, while minimum monthly rainfall varies between 0.5 – 1.0 mm and is recorded in February. November and March always experiences the highest mean monthly temperature (30 - 40°C) while the highest mean sunshine hours (5.5 – 6.5) and lowest mean sunshine hour (2 – 2.5) are recorded in December and August respectively. Though all the year round, the relative humidity is generally high but the highest relative humidity is recorded during the wet seasons. The soils originate from coastal sediments and have been classified as acrisol (FAO/UNESCO) and ultisol (USDA). The soil has soil related constraints to the productivity of soil such as low organic matter content and low inherent fertility (Onwudike et al., 2017), high soil acidity (both natural and fertilizer induced), low activity clay (Onwudike et al., 2015), poor water holding capacity of soil, nutrient depletion and high vulnerability to erosion (Opara-Nadi, 2000).

Description of the Land Use Systems

Eleven land use systems were studied which include natural or primary forest (NF) and bush fallow or secondary forest (BF), alley cropping (AC), oil palm plantation (OP), alley cropping with bread fruit (*Treculia Africana L.*) alone (TA), alley cropping with mango (*Magifera indica L.)* alone (MI), alley cropping with acioa (*Dactyldenia barteri L.*) alone (DB), alley cropping with African oil bean (*Pentaaclethra macropylla L.*) alone (PM), continuous Cassava (*Manihot esculenta Crantz*) cropping with fertilizer (FC) and continuous Cassava

(*Manihot esculenta Crantz*) cropping without fertilizer (UC) plots. Sample collections were replicated three times within the same geographic location and of the same geologic material. Details of site and vegetation characteristics of these land use systems are summarized here.

1. Natural forest (NF)- complex with predominant species of acioa (*Dactyldenia barteri L.*) and African oil bean (*Pentaclethra macrophylla L.*) plus shrubs and grasses.
2. Bush fallow (BF)- secondary regrowth (5years) with acioa (*D. barteri* L.), shrubs e.g. Siam weed (*Chromolaena adorata* L.). African marigold (*Aspilia Africana* L.) and grasses e.g. guinea grass (*Panicum maximum* L.) as predominate species. The land use prior to bush fallow was 4 years continuous cassava maize intercropping.
3. Alley cropping with MPTs (AC)- mature (10 years) of fruits trees of bread fruit (*Treculia africana* L.), irvingia (*Irvingia gabonensis L.*) and African pear (*Dacroydes edulis L.*) planted in 8 m row arrangement and this was the distance between cultivated alleys. The land use prior to alley cropping was 4 years continuous cassava (uninterrupted) cropping.
4. Oil palm plantation (OP) mature (30 years) of palm trees (*Elaeis guinensis L.*).
5. Alley cropping with bread fruit (*Treculia Africana L.)* alone (TA)- same age and arrangement as 3.
6. Alley cropping with irvingia *(Irvingia gabnensis L.*) alone (IG)- same as 3.
7. Alley cropping with mango (*Magnifera indica L.)* alone (MI)- same as 3.
8. Alley cropping with acioa (*Dactyldenia barteri L.)* alone (DB) - same as 3.
9. Alley cropping with African Oil bean (*Pentaaclethra macropylla L.*) alone (PM) - same as 3.
10. Sole cropping of cassava (*Manihot esculenta Crantz*), without inorganic fertilizer (UC) -7 years.
11. Same as 10 but with inorganic fertilizer application (FC).

Soil Sampling and Chemical Analysis

For all land use systems, soil texture of the topsoil and slope position (middle slope) within transect were used as criteria to locate sampling areas. This was necessary in order to minimize error in data interpretation arising from spatial variability. Soil sampling was done in replicated 100 m by 100 m quadrants in each land use type and in each sample location. Each quadrant was subsequently divided into 10 sub quadrants, each measuring 10 m by 10 m from which three cores samples were randomly selected. Soil sampling sites were selected on the basis of uniformity in characteristics which included slope, elevation, soil type and texture as well as present land use. Disturbed (composite) samples and undisturbed (core) samples were sampled with the use of cylindrical metal core with diameter of 5 cm and 5cm height and these were taken in three replicate from each of 0- to 10, 10- to 20 and 20- to 40 cm depths. The core samples were taken with a hammer-driven sampler. Physical properties (bulk density and total porosity) were obtained using core sampler as described by Grossman and Reinsch (2002), while the augar soils were used to determine chemical properties (pH), organic C, total N, exchangeable acidity and cations (K, Ca, Mg, Na, Mn and Al). Chemical analyses were done in the Soil Science laboratory of Buesgen-Institute of Temperate and Boreal Ecosystems, University of Goettingen, Germany. The pH soil was measured in deionized 1:1 soil-water-extract using ICP-Mass spectrometry. Organic C and concentrations of total N were obtained by high-temperature catalytic combustion using a Heraeus-CHN Analyzer (Vario Max, Elementar Analysen systeme, Germany). Exchangeable cations were measured using ICP-Mass spectrometry after displacement in I M NH_4CI solution, CEC by summation of exchangeable cations and base saturation from CEC and cation values. The masses of SOC and TN on an area basis (Mg ha^{-I}) were obtained by multiplying SOC and TN in grams per 100 g by the bulk density (Mg m^{-3}), soil depth (m) and area (10,000 m^2). The C:N ratio was gotten by dividing the soil organic carbon the values of total nitrogen. Significance of differences for the different soil parameters among land uses and the depths was determined using analysis of variance (ANOVA) with Statistical Analysis Systems (SAS, 2001). Significance was assigned to probability level of p = 0.05.

Results

Soil Bulk Density

Forest and forest derived land use systems had significant effect on soil bulk density (Table I) in the 0 to 10, 10 to 20 and 20 to 40 cm depths. In all these depths, lowest bulk density was obtained for cassava based systems (UC and FC). In the 0- to 10- cm depths, the NF, TA, PM, UC and FC systems had bulk density values lower than 1.40 g cm^{-3}, while the BF, AC, OP, IG, MI, and DB systems had 21 values higher than 1.40 g cm^{-3}. In the 10 to 20 and 20 to 40 cm depths, bulk density did not differ significantly between the NF, BF, AC, OP, IG, MI, DP, and PM systems. Generally, bulk density increased with soil depths.

Table 1. Soil bulk density of 0–10, 10 – 20 and 20 – 40 cm depths under different land use system

Land use system	Soil bulk density (Mg m^{-3}) Soil depth (cm)		
	0 – 10 cm	10 – 20 cm	20 – 40 cm
Natural forest (NF)	1.37 ± 0.06	1.52 ± 0.11	1.56 ± 0.18
Bush fallow (BF)	1.53 ± 0.10	1.59 ± 0.13	1.71 ± 0.12
Alley cropping with MPTs (AC)	1.48 ± 0.08	1.62 ± 0.09	1.67 ± 0.15
Oil palm plantation (OP)	1.42 ± 0.11	1.64 ± 0.09	1.69 ± 0.09
Alley cropping (TA)	1.36 ± 0.07	1.43 ± 0.10	1.49 ± 0.06
Alley cropping (IG)	1.43 ± 0.09	1.53 ± 0.12	1.62 ± 0.11
Alley cropping (MI)	1.53 ± 0.15	1.66 ± 0.18	1.69 ± 0.12
Alley cropping (DB)	1.55 ± 0.13	1.62 ± 0.14	1.64 ± 0.12
Alley cropping (PM)	1.35 ± 0.08	1.57 ± 0.10	1.58 ± 0.09
Unfertilized cassava (UC)	1.25 ± 0.06	1.29 ± 0.08	1.44 ± 0.06
Fertilized cassava (FC)	1.34 ± 0.10	1.35 ± 0.07	1.47 ± 0.10

MPTs(AC) = Alley cropping with multi-purpose trees, TA= *Treculia Africana .L.*, IG =*Irevingia ganensis L.*, MI = *Magnifera indica. L.*, DB = *Dactyldenia barteri. L*, PM = *Pentaclethra macropylla. L*, UC = cassava Cropping without fertilizer application, FC= cassava cropping with fertilizer application

Soil pH

The pH values of the soil over the total sampled depths were acidic and significantly different among the different land use systems (Table 2, 3, 4). In all three depths, soil pH was highest for OP system and lowest for NF system. Generally, soil pH for the 0 to 10, 10 to 20 and 20 to 40 cm depths did not show any definite trend and did not differ appreciably for each land use.

Table 2. Soil characteristics of the 0 – 10 cm depth under land uses

Soil characteristics	NF	BF	AC	OP	TA	IG	MI	DB	PM	UC	FC	$LSD_{0.05}$
pH (H_2O)	4.10	4.48	4.50	5.45	4.28	4.80	4.55	4.58	4.50	4.63	4.37	0.30
Potassium, cmol kg^{-1}	0.41	0.13	0.13	0.23	0.087	0.095	0.087	0.11	0.13	0.13	0.17	0.10
Calcium, cmol kg^{-1}	1.55	0.40	1.09	2.20	0.16	1.42	0.75	1.96	1.15	0.49	0.81	0.85
Magnesium, cmol kg^{-1}	0.66	0.082	0.27	0.62	0.070	0.034	0.17	0.44	0.23	0.10	0.078	0.27
Sodium, cmol kg^{-1}	0.17	0.067	0.090	0.059	0.043	0.027	0.028	0.047	0.055	0.041	0.061	0.022
Manganese, cmol kg^{-1}	0.084	0.017	0.046	0.039	0.025	0.096	0.060	0.054	0.017	0.020	0.015	0.056
Aluminium, cmol kg^{-1}	3.77	1.99	1.81	0.030	2.58	0.88	1.58	1.26	1.50	2.28	2.34	1.26
Exch. Acidity, cmol kg $^{-1}$	4.10	2.05	1.99	0.030	2.69	0.92	1.65	1.50	2.20	2.36	2.42	1.56
CEC, cmol kg^{-1}	7.05	2.76	3.57	3.16	3.10	2.59	2.78	4.14	3.09	3.15	3.55	1.76
Base saturation, %	39.57	24.00	43.83	97.75	11.61	64.67	36.51	61.76	28.33	24.16	31.24	12.21
Al saturation, %	53.58	72.10	50.70	0.95	83.23	30.13	56.83	30.43	61.83	72.38	65.92	21.02

LSD = least significant difference, CEC =cation exchange capacity, NF = Natural forest BF= bush fallow, AC = alley cropping, OP = oil palm plantation, TA= *Treculia Africana .L.*, IG =*Irevingia ganensis L.*, MI = *Magnifera indica. L.*, DB = *Dactyldenia barteri. L*, PM = *Pentaclethra macropylla. L*, UC = Cropping without fertilizer application, FC= cropping with fertilizer application

Table 3. Soil characteristics of the 10 – 20 cm depth under land uses

Soil characteristics	NF	BF	AC	OP	TA	IG	MI	DB	PM	UC	FC	$LSD_{0.05}$
pH (H_2O)	4.13	4.52	4.44	5.53	4.21	4.71	4.53	4.66	4.37	4.54	4.51	0.36
Potassium, cmol kg^{-1}	0.27	0.092	0.11	0.18	0.082	0.090	0.063	0.10	0.069	0.15	0.19	0.12
Calcium, cmol kg^{-1}	0.25	0.29	0.65	2.18	0.067	0.160	0.24	0.47	0.10	0.13	0.44	0.55
Magnesium, cmol kg^{-1}	0.13	0.038	0.095	0.58	0.030	0.041	0.045	0.097	0.042	0.063	0.042	0.17
Sodium, cmol kg^{-1}	0.092	0.091	0.048	0.060	0.019	0.049	0.026	0.050	0.028	0.068	0.079	0.024
Manganese, cmol kg^{-1}	0.013	0.016	0.010	0.029	0.010	0.013	0.018	0.014	0.004	0.012	0.018	0.023
Aluminium, cmol kg^{-1}	4.72	2.08	3.76	0.12	3.10	2.60	2.73	2.30	2.27	2.70	3.05	1.47
Exch. Acidity, cmol kg $^{-1}$	4.88	2.13	0.91	0.12	3.20	2.20	2.78	2.36	2.37	2.78	3.12	1.22
CEC, cmol kg^{-1}	5.68	2.62	3.84	3.14	3.14	2.70	3.17	3.06	2.60	3.38	3.89	1.01
Base saturation, %	13.01	17.76	23.62	94.26	5.56	18.00	11.93	23.20	9.33	20.06	19.05	9.42
Al saturation, %	83.10	79.39	71.88	3.82	90.91	78.80	86.12	74.68	82.27	79.88	78.41	19.46

LSD = least significant difference, CEC =cation exchange capacity, NF = Natural forest BF= bush fallow, AC = alley cropping, OP = oil palm plantation, TA= *Treculia Africana .L.*, IG =*Irevingia ganensis L.*, MI = *Magnifera indica. L.*, DB = *Dactyldenia barteri. L*, PM = *Pentaclethra macropylla. L*, UC = Cropping without fertilizer application, FC= cropping with fertilizer application

Table 4. Soil characteristics of the 20 - 40 cm depth under land uses

Soil characteristics	NF	BF	AC	OP	TA	IG	MI	DB	PM	UC	FC	$LSD_{0.05}$
pH (H_2O)	4.14	4.42	4.55	5.46	4.32	4.51	4.69	4.59	4.40	4.60	4.45	0.39
Potassium, cmol kg^{-1}	0.25	0.12	0.058	0.16	0.060	0.090	0.053	0.061	0.051	0.11	0.13	0.09
Calcium, cmol kg^{-1}	0.16	0.47	0.63	1.40	0.020	0.16	0.34	0.32	0.040	0,33	0.34	0.76
Magnesium, cmol kg^{-1}	0.080	0.062	0.055	0.43	0.021	0.041	0.030	0.053	0.028	0.074	0.038	0.16
Sodium, cmol kg^{-1}	0.099	0.068	0.038	0.050	0.012	0.050	0.033	0.042	0.016	0.039	0.093	0.026
Manganese, cmol kg^{-1}	0.008	0.022	0.004	0.016	0.009	0.013	0.012	0.010	0.005	0.007	0.011	0.091
Aluminium, cmol kg^{-1}	4.86	3.29	3.20	0.33	2.63	2.60	2.58	2.49	2.52	2.79	3.41	1.44
Exch. Acidity, cmol kg $^{-1}$	4.97	3.37	3.31	0.33	2.70	2.64	2.64	2.69	2.59	2.87	3.49	1.36
CEC, cmol kg^{-1}	5.59	4.13	4.10	2.38	2.18	2.98	3.11	3.10	2.73	3.42	4.05	1.71
Base saturation, %	10.63	17.49	18.99	85.26	3.99	11.28	14.78	15.49	4.97	15.80	13.72	8.16
Al saturation, %	86.94	79.66	78.05	13.87	93.59	86.62	82.96	80.32	92.31	81.58	84.20	24.06

LSD = least significant difference, CEC =cation exchange capacity, NF = Natural forest BF= bush fallow, AC = alley cropping, OP = oil palm plantation, TA= *Treculia Africana .L.*, IG =*Irevingia ganensis L.*, MI = *Magnifera indica. L.*, DB = *Dactyldenia barteri. L*, PM = *Pentaclethra macropylla. L*, UC = Cropping without fertilizer application, FC= cropping with fertilizer application

Exchangeable Potassium, Calcium, Magnesium, Sodium, Manganese and Aluminium

Significant differences among land uses were found in the measured soil characteristics in the 0 to 10 cm depth (Table 2), 10 to 20 cm depth (Table 3), and 20 to 40 cm depth (Table 4). In addition, differences between the highest and lowest values of each of these characteristics ranged widely. For example, in the 0 to 10 cm layer, the highest value of K was 0.41 cmol kg^{-1} (NF) and the lowest was 0.076 cmol kg $^{-1}$ (IG), showing a difference of 439% for the variability in K content that existed within land uses. Similarly, the highest value of Ca was 2.20 cmol kg^{-1} for OP and the lowest was 0.16 for TA system, showing in difference of 128% and also illustrating a high variability in Ca content among the different land use systems.

Exchangeable K, Na and Al in all three depths were highest for NF, while Ca was highest for OP, when compared with the other land use systems. Exchangeable Ca and Mg in all three depths were lowest for TA, while exchangeable Al was lowest for OP system in comparison to the other systems. The study found that the content of exchangeable K, Ca, Mg, Na and Mn decreased with increase in the depth of the soil, while the content of exchangeable Al increased with depth. For example, under the NF system, exchangeable K, Ca, Mg, Na and Mn showed a decrease of 39.90, 88, 42 and 90 percent respectively from the 0 to 10 cm to the 20 to 40 cm depth. Exchangeable Al showed an increase of 22 percent between these two depths. Similarly, for the OP systems, the decrease in the concentrations of exchangeable K, Ca, Mg, Na and Mn was 30, 42, 31, 44 and 59 percent respectively, while the increase in Al concentration was 91 percent from the 0 to 10 cm to the 20 to 40 cm depth. These results showed that nutrient dynamics under the land use systems varied considerably.

Exchangeable Acidity, Al saturation, CEC and base saturation

Exchangeable acidity and CEC were significantly highest in the NF system in the 0 to 10, 10 to 20 and 20 to 40 cm depths when compared with the other land use systems (p=0.05) (Tables 3, 4, 5). Similarly, base saturation and Al saturation were higher in the OP and TA systems respectively in all three depths than in any of the other land use systems (Table 2, 3, 4). On the other hand, in all three depths, exchangeable acidity, CEC and Al saturation were lowest in the OP system, while base saturation was lowest in the TA system, when compared with the other systems. Averaged over the three depths, exchangeable acidity was 4.65, 3.01, 2.86, 2.67, 2.52, 2.36, 2.21, 2.18, 1.92 and 0.16 cmol kg^{-1} for NF, FC, TA, AC, UC, BF, MI, PM, DB, IG and OP systems respectively. Similarly, averaged over the three depths, CEC was of the order NF > AC > FC > DB > UC > BF > TA > MI > PM > IG > OP systems. As with exchangeable acidity and CEC, base saturation and Al saturation averaged over the three depths did not follow any definite trend among the different land systems. Base saturation and Al saturation values varied between 7.05% (TA) to 92.50% (OP) and 6.22% (OP) to 89.24% (TA) respectively.

Soil C and N Concentration, C: N ratio and C and N Storage

Conversion of natural forest to agricultural land use led to a decrease in soil organic carbon (SOC) and total N content in the 0-to 10- cm depth (Table 5), 10- to 20- cm depth (Table 6) and 20- to 40- cm depth (Table 7) but the largest contrasts between the land use systems were found in the top depth increment (0 – 10 cm) than the last two increments (p = 0.05). In the 0 to 10 cm depth, SOC concentration was highest (33.7 gkg^{-1}) for NF system and lowest (9.5 g kg^{-1}) for IG system. In the 10- to 20- cm depth, SOC content was highest (17.6 g kg^{-1}) for NF system and lowest (8.2 gkg^{-1}) for DB system. Similarly, in the 20- to 40- cm depth, SOC content was highest (14.7 gkg^{-1}) for both the NF and BF systems and lowest (6.6 gkg^{-1}) for MI system. As with SOC content, TN content was significantly different among the land use systems (p= 0.05), also decreased with depth and with largest contrasts among the land use systems found in the 0 to 10 cm depths than in the other two depth increments.

Table 5. Soil C and N content, C:N ratio and C and N storage of the 0 – 10 cm depth under different land use systems

Land use system	Carbon content g kg^{-1}	Nitrogen Content g kg^{-1}	C:N	C storage Mgha^{-1}	N Storage Mgha^{-1}
Natural Forest (NF)	33.7	2.6	12.9	46.9	3.6
Bush fallow (BF)	10.8	0.8	12.7	16.5	1.3
Alley cropping with MPTs (AC)	13.7	1.1	12.9	19.8	1.5
Oil palm plantation (OP)	13.7	1.1	12.9	19.8	1.5
Alley cropping (TA)	12.8	0.9	13.8	16.8	1.1
Alley cropping (IG)	9.5	0.7	13.0	13.6	1.1
Alley cropping (MI)	10.3	0.8	12.9	15.8	1.3
Alley cropping (DB)	15.9	1.1	14.3	24.8	1.7
Alley cropping (PM)	13.3	1.2	11.4	18.0	1.6
Unfertilized cassava (UC)	12.9	1.0	12.5	16.1	1.3
Fertilized cassava (FC)	12.6	1.0	12.5	17.0	1.4
LSD (0.05)	3.9	0.6	3.1	6.8	0.5

NF = Natural forest BF= bush fallow, MPTs(AC) = Alley cropping with multi-purpose trees, OP = oil palm plantation, TA= Treculia Africana .L., IG =Irevingia ganensis L., MI = Magnifera indica. L., DB = Dactyldenia barteri. L, PM = Pentaclethra macropylla. L, UC = Cropping without fertilizer application, FC= cropping with fertilizer application

Table 6. Soil C and N content, C:N ratio and C and N storage of the 10 – 20 cm depth under different land use systems

Land use system	Carbon content g kg^{-1}	Nitrogen Content g kg^{-1}	C:N	C storage Mgha^{-1}	N Storage Mgha^{-1}
Natural Forest (NF)	17.6	1.3	13.2	26.7	2.1
Bush fallow (BF)	9.2	0.7	12.5	14.6	1.1
Alley cropping with MPTs (AC)	11.3	1.1	10.0	18.4	1.4
Oil palm plantation (OP)	12.6	1.0	13.0	19.1	1.5
Alley cropping (TA)	12.3	1.0	12.7	17.6	1.3
Alley cropping (IG)	9.2	0.8	12.1	14.1	1.1
Alley cropping (MI)	8.9	0.8	11.7	14.8	1.3
Alley cropping (DB)	8.2	0.7	12.4	13.2	1.1
Alley cropping (PM)	9.3	0.8	12.2	14.8	1.3
Unfertilized cassava (UC)	10.3	0.8	11.2	14.8	1.3
Fertilized cassava (FC)	12.9	1.0	12.9	16.4	1.3
LSD (0.05)	2.4	0.4	3.5	5.3	0.5

NF = Natural forest BF= bush fallow, MPTs(AC) = Alley cropping with multi-purpose trees, OP = oil palm plantation, TA= *Treculia Africana .L.*, IG =*Irevingia ganensis L.*, MI = *Magnifera indica. L.*, DB = *Dactyldenia barteri. L*, PM = *Pentaclethra macropylla. L*, UC = Cropping without fertilizer application, FC= cropping with fertilizer application

Table 7. Soil C and N content, C:N ratio and C and N storage of the 20 – 40 cm depth under different land use systems

Land use system	Carbon content g kg^{-1}	Nitrogen Content g kg^{-1}	C:N	C storage Mgha^{-1}	N Storage Mgha^{-1}
Natural Forest (NF)	14.7	1.1	13.3	46.0	3.5
Bush fallow (BF)	14.7	1.0	14.7	50.1	3.5
Alley cropping with MPTs (AC)	8.6	0.7	12.8	28.6	2.3
Oil palm plantation (OP)	7.6	0.6	12.4	26.2	2.1
Alley cropping (TA)	11.2	0.8	13.4	33.2	2.5
Alley cropping (IG)	8.3	0.6	13.2	27.0	2.1
Alley cropping (MI)	6.6	0.7	10.0	22.3	2.2
Alley cropping (DB)	8.1	0.6	13.6	26.7	2.0
Alley cropping (PM)	7.5	0.7	11.2	23.6	2.2
Unfertilized cassava (UC)	7.6	0.6	12.3	22.0	1.9
Fertilized cassava (FC)	11.0	0.9	12.7	32.3	2.6
LSD (0.05)	7.1	0.7	4.4	7.9	0.8

NF = Natural forest BF= bush fallow, MPTs(AC) = Alley cropping with multi-purpose trees, OP = oil palm plantation, TA= *Treculia Africana .L.*, IG =*Irevingia ganensis L.*, MI = *Magnifera indica. L.*, DB = *Dactyldenia barteri. L*, PM = *Pentaclethra macropylla. L*, UC = Cropping without fertilizer application, FC= cropping with fertilizer application

In the 0 to 10 cm depth, TN content was highest (2.6 g kg^{-1}) for NF and lowest (0.7g kg^{-1}) for IS system. In the 10 to 20 cm depth, TN concentration was highest (1.3 g kg^{-1}) for NF and lowest (0.7g kg^{-1}) for BF and DB systems, while in the 20 to 40 cm, TN content was highest (1.1 g kg^{-1}) for NF and lowest (0.6 g kg^{-1}) for OP, IG, DB and UC systems. Soil organic C storage was significantly greater (p = 0.05) in NF system than in any of the forest derived land use systems in the 0 to 10 and 10 to 20 cm depths (Tables 5 and 6 respectively) while in the 20 to 40 cm depth (Table 7), SOC storage was greater in the BF system than in any of other land use systems. For example, in the 0 to 10 cm depth, SOC storage was highest (46.9 Mgha^{-1}) in the NF system and lowest (13.6 Mg ha^{-1}) in the IS system. Compared to the NF system, decrease in SOC storage in this depth was 47.1, 57.8, 57.8, 61.6, 63.8, 64.8, 65.7, 66.3 and 70.6 percent for DB, AC, OP, PM, FC, TA, BF, UC, MI and IG systems respectively. In the 10- to 20- cm depth, SOC storage was highest (26.7 Mg ha^{-1}) for NF and lowest (13.2 Mg ha^{-1}) for DB system, while in the 20- to 40- cm depth, SOC storage was highest (50.1 Mgha^{-1}) for BF and lowest (22.0 Mgha^{-1}) for UC system.

These results showed that SOC storage in 0 to 10 and 10 to 20 cm depths was significantly higher than in five years of bush fallow (BF), eight years of alley cropping with MPTs (AC) and thirty years of oil palm plantation (OP). In contrast, SOC storage in 20- to 40- cm depth was insignificant in NF and BF systems, while SOC storage in these systems was higher than in any of the other systems. Soil organic C storage in the 0 to 10 and 10 to 20 cm depths did not differ between UC and FC plots but in the 20 to 40 cm depth, the FC plot had significantly higher SOC stock than the UC plot (32.3 vs. 22.0 Mgha^{-1}).

Soil TN storage was higher ($p = 0.05$) in NF system than any of the other land use systems in the 0 to 10 and 10 to 20 cm depths (Tables 5 and 6 respectively), but in the 20 to 40 cm depth (Table 7), TN storage was equal in the NF and BF systems and was higher in these two systems than in any of the other land uses. In the 0 to 10 cm depths, total N storage ranged from 1.1 Mg ha^{-1} in the TA and IS systems to 3.6 Mg ha^{-1} in the NF system, in the 10 to 20 cm depth, the range was from 1.1 Mg ha^{-1} (BF, IS and DB systems) to 2.1 Mg ha^{-1} (NF system), while in the 20 to 40 cm, it ranged from 1.9 Mg ha^{-1} in the UC system to 3.5 Mg ha^{-1} in both the NF and BF systems. For the 0 to 10 cm depth, TN storage decreased by 69.4, 69.4, 66.7, 63.9, 61.1, 58.3, 55.6, and 52.8 percent for the TA, IG, MI, BF, UC, FC, OP, AC, PM and DB systems respectively when compared to the NF system. In the 0 to 10 and 10 to 20 cm depths, TN storage in NF was significantly higher than in five years bush fallow, eight years of alley cropping and thirty years oil palm plantation but in the 20 to 40 cm TN storage was the same for BF and NF systems. Total C decreased with depth (with 10 cm depth increment) in all the land uses, while total N mass did not follow this trend but was more or less uniform in the depth increments. Thus, a difference in total N mass was less detectable as with total C mass.

The C: N ratios for the 0 to 10 cm depth (Table 5), 10 to 20 cm depth (Table 6) and 20 to 40 cm depth (Table 7) did significantly differ ($p = 0.05$) when compared to the different land uses and did not follow any definite trend. The C: N ratios ranged from 11.4 (PM system) to 13.8 (TA system) in 0 to 10 cm depth, 10.0 (AC system) to 13.2 (NF system) in 10 to 20 cm depth and 10.0 (MI system) to 14.7 (BF system). The results also showed that C: N did not correlate with either C and N content or SOC and TN storage in the land use systems, even though detectable changes in these soil properties were very high, ranging between 47% to 71% for SOC storage and between 52% to 69% for TN storage in the 0 to 10 cm depth for example.

The total SOC and TN storage (Mg ha^{-1}) in the whole soil pedon (0 - 40 cm) are presented in Table 8. When compared to NF system, total SOC and TN storage showed a decrease in percent of 32.1 and 35.9 respectively for BF, 44.1 and 43.5 for AC, 45.6 and 44.6 for OP, 43.5 and 46.7 for TA, 54.3 and 53.3 for IS, 55.8 and 48.9 for MI, 45.9 and 47.8 for DB, 52.2 and 44.6 for PM, 52.9 and 51.1 for UC and 45.3 and 42.4 for FC. On the average, the total SOC and TN storage in the 0 – 40 cm depth decreased by 48 and 46 percent respectively due to forest conversion to agricultural land use systems.

Table 7. Total C and N storage for the 0 – 40 cm depth under different land use systems

Land use system	C storage, Mgha^{-1}	N Storage, Mgha^{-1}
Natural Forest (NF)	119.6	9.2
Bush fallow (BF)	81.2	5.9
Alley cropping with MPTs (AC)	66.8	5.2
Oil palm plantation (OP)	65.1	5.1
Alley cropping (TA)	67.6	4.9
Alley cropping (IG)	54.7	4.3
Alley cropping (MI)	52.9	4.7
Alley cropping (DB)	64.7	4.8
Alley cropping (PM)	57.2	5.1
Unfertilized cassava (UC)	52.9	4.5
Fertilized cassava (FC)	65.4	5.3
LSD (0.05)	13.1	0.9

NF = Natural forest BF= bush fallow, MPTs(AC) = Alley cropping with multi-purpose trees, OP = oil palm plantation, TA= *Treculia Africana .L.*, IG =*Irevingia ganensis L.*, MI = *Magnifera indica. L.*, DB = *Dactyldenia barteri. L*, PM = *Pentaclethra macropylla. L*, UC = Cropping without fertilizer application, FC= cropping with fertilizer application

Discussion

The lower bulk density and higher porosity in the 0 to 10, 10 to 20 and 20 to 40 cm depths of soils under continuous cassava cultivation than soils under forest plantation and alley cropping might be ascribed to the loosening of the topsoil by the tuberous roots of cassava over time. This effect might have overshadowed the effect of continuous cultivation on loss of SOC and reduction in the aggregation of soil both of which would otherwise result in increased bulk density. Opara-Nadi and Lal (1987) observed that the development of tuberous roots under cassava in the topsoil (0-20 cm) led to a decrease in bulk density which is intimately connected with increased porosity and alteration of pore size distribution.

The acidic nature of the soils under all the land uses was more a reflection of the nature of the parent material (quartz rich, coarse textured and strongly leached) as reported by Onwudike (2015) than the effect of land use systems. The higher soil pH in the 0 to 10, 10 to 20 and 20 to 40 cm depths under oil palm plantation than any of the other systems may be attributed to high calcium content, high base saturation and low aluminium content. The long-term inorganic fertilizer input in the FC system did not affect the soil pH as there was no effect in pH between the fertilized and unfertilized and cassava plots.

The higher values of exchangeable K, Na and AI, CEC and acidity under forest soil than soils under any of the other land use systems as well as the relatively high values of Ca and Mg under forest soil demonstrate the high capacity of forest soils to conserve and enhance SOM, which in turn, has positive implications on the conversation of nutrients. The result of this study confirms those of other studies on tropical ecosystems and other ecosystems (Fernandez et al., 1997; Sanchez, 2000; McGrath et al., 2001; Lal, 2005; Jelinski and Kucharik, 2009; Nair et al., 2009). The relatively lower levels of exchangeable nutrients and acidity as well as CEC under bush fallow, agro-forestry and oil palm plantation than primary forest demonstrate the fact that the recovery of these systems in terms of nutrient addition is a rather slow process. Similar studies showed that the rate of recovery of bush fallows following forest clearing in terms of nutrient build-up and fertility status is rather a slow process have been reported (Brown and Lugo, 1990; Szott and Palm, 1996). These studies also showed that rate of recovery of bush fallows and fertility status depends on a number of factors such as climate, type of secondary vegetation, rate of turn-over of SOM as well as nutrient and fertility levels at the onset of fallow regeneration. These factors were not examined in study but it may suffice to mention here that the tree species in the alley cropping systems were not leguminous tress capable of fixing atmospheric nitrogen and also having high rate of SOM turn-over in the soil. The very high base saturation in the 0–40 cm depth of soil under OP system demonstrates the high levels of exchangeable acidity and AI saturation under this system. Exchangeable Ca, Mg and K in that order contributed to the high base saturation of soil under OP system. Both Ca and Mg distributions in the OP system as well as K distribution in the NF system were strongly stratified with depth in these two systems, which had the highest concentrations of these elements in the top 40 cm depth in comparison to the other land use systems. These three elements were dominant in the CEC level in the soil. The effect of CEC was perhaps a more important action than exchangeable cations and acidity in determining the nutrient status and overall fertility of soils under most of the land use systems.

As was reported in previous studies (Ellert and Bettany, 1995; Blanco-Canqui and Lal, 2005; Jelinski and Kucharik, 2009), SOC, TN content and storage were calculated on an area basis rather than on mass basis. Thus, differences in soil bulk density which was large and significant had a large influence on SOC and TN content and storage under the different land use systems in the study area. The potentially high SOC and TN storage in the entire topsoil (0–40 cm), ranging from 52.9 to 119.6 Mgha^{-1} for SOC and 4.3 to 9.2 Mgha^{-1} for TN showed that between land use systems different soil bulk density values dramatically affected calculations of differences in SOC and TN storage. Similar observations have been made by other workers (Brown and Lugo, 1990; Puget and Lal, 2005; Blanco-Canqui and Lal, 2008; Jelinski and Kucharik, 2009; Geissen, 2009) in studies involving land use alone, tillage alone or land use and tillage in the US forest and cropland soils and also in studies involving mulching and tillage, tillage and organic amendments or soil and crop management practices in south-eastern Nigeria (Ohaneje, 2002, Kirby and Potvin, 2007). When natural forest was converted into cultivation, SOC and TN storage for a depth of 0- to 10- cm was reduced significantly with an average of 63 and 62 percent respectively relative to SOC and TN storage of the natural forest land. In the whole soil pedon (0–40 cm), total SOC and TN storage decreased by an average of 48 and 46 percent respectively for all forest derived land use systems due to forest change to agriculture. Similar results showing a drop of SOC and TN stock or storage have been reported for other studies in different ecological zones. For example, Kern and Johnson (1993) and Murty et al. (2002) evaluated the decrease of SOC stock in the major US cropland soils at approximately 16% and 22 – 25% respectively upon conversion from forest to crop. Similarly, Guo and Gifford

(2002) reported that soils lost 42% of their SOC stock upon forest conversion. Carter et al. (1998) reported that cultivation decreased the mass of organic C (35%) and total N (10%) in the soil profile of Podzolic soils.

The non-significant effect of land use systems on C:N ratio in the study area is in agreement with the findings of Jelinski and Kucharik (2009) and Geissen et al. (2009) in other locations even though the result of land use change from forest to agriculture on SOC and TN content and storage in all three depths was very detectable and significant. However, the result of this study deviated from the findings of Franzluebbers et al. (2002) and Puget and Lal (2005) which reported that forest soils have higher C:N ratios than agricultural soils.

Conclusion

The findings of this study demonstrate a consistent decrease in soil organic carbon (SOC) and total nitrogen (TN) concentrations and storage when natural forests are converted to agriculture in south-eastern Nigeria. These results are in agreement with previous studies conducted in different ecological zones. The study reveals that forest ecosystems possess a higher capacity to retain exchangeable potassium (K), sodium (Na), aluminum (AI), cation exchange capacity (CEC), and acidity compared to other land systems. Moreover, the relatively high concentrations of calcium (Ca) and magnesium (Mg) under the forest indicate the forest's ability to conserve and enhance soil organic matter (SOM) and nutrient content.

The research also demonstrates a significant decline in total SOC and TN storage (0 – 40 cm depth) by an average of 48% and 46%, respectively, for all forest-derived land use systems following conversion to agriculture. These results highlight the substantial capacity of natural forests to sequester and store large amounts of SOC and TN, surpassing the values observed in forest-derived land uses. Additionally, the study reveals that 5, 10, and 30 years of forest regrowth (bush fallow), alley cropping with multipurpose trees (MPTs), and oil palm plantation, respectively, were insufficient in restoring fertility levels similar to those found in the natural forest.

Based on the findings, it can be concluded that continuous cultivation of cassava, with or without inorganic fertilizer inputs, leads to a decrease in SOC and TN stocks in the soil. Overall, the conversion of forest to agriculture in the study area significantly impacted key soil chemical attributes associated with fertility of soil, including SOC, CEC and total nitrogen. These results emphasize the need for further research on the potential of agroforestry systems in storing SOC and TN in the rainforest zones. Additionally, long-term comparative studies investigating carbon and nitrogen sequestration under natural forests, grasslands, and agroforestry systems are warranted.

In conclusion, this study sheds light on the consequences of land use change from forest to agriculture on soil chemical properties and nutrient dynamics. It underscores the importance of preserving natural forests for their significant role in carbon and nitrogen storage, while also emphasizing the potential of agroforestry systems as viable alternatives. The findings provide valuable insights for sustainable land management practices in similar ecological zones and suggest avenues for future research.

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