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Differential Impact of Land Use Types on Soil Productivity Components in Two Agro-ecological Zones of Southern Ghana

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Abstract

The maintenance of soil productivity is important for sustained crop yield in low-input systems in the tropics. This study investigated the impact of four different land use types, namely, maize and cassava cropping, woodlot/plantations, and natural forests on soil productivity components, especially soil carbon accretion, at six sites within two agro-ecological zones of southern Ghana. Soil properties were significantly different between sites and ecological zones. The coastal savanna zones, which is a low rainfall zone had relatively lower soil carbon storage than the high rainfall forest-savanna transition zone. Soil productivity conditions in the later zone were much more favorable for cropping than the former. Land use types significantly affected the soil carbon (*SOC*) storage within the two ecological zones. In the low rainfall zone, soil carbon accretion by maize cropping, cassava cropping, and plantations were 48%, 54%, and 60%, respectively, of the forest carbon stock (47,617 kg/ha). In the transition zone, the soil carbon accretion was over 90% of the forest value (48,216 kg/ha) for all land use types. In effect use of land use types in maintaining soil productivity must consider the conditions in a given ecological zone.

Keywords

Agro-ecology · Land use · Soil carbon stock · Soil productivity · Soil properties

Introduction

Soil organic carbon (*SOC*) is a major component of productivity in low-input cropping systems of the tropics. Soil carbon influences the physical, chemical, and biological properties of the soil. Many studies have indicated that the reduction in the *SOC* can result in significant decrease in the available water capacity (Hudson 1994), structural deterioration, and an increased bulk density (Shu et al. 2015). Also, the contribution of the *SOC* to soil fertility maintenance is also well established. Crop yield reduction is often associated with *SOC* losses, largely because the *SOC* is a major reservoir of nutrients, especially in the tropics where external inputs continue to remain low (Sanchez et al. 2009). Estimates by Lal (2006) indicated that maize yield could decline by 30–300 kg ha^{-1} for every ton ha^{-1} of *SOC* in the root zone. Regarding soil biology, the *SOC* is a major source of nutrition and energy for microbial life. Some authors describe the *SOC* as the "... life blood" of tropical soils (Acquaye 1989). Though the *SOC* plays a dominant role in tropical agriculture, other soil properties may also enhance the overall productivity. Nutrients elements such as nitrogen, which is largely derived from organic matter mineralization, phosphorus from rock minerals, and the overall cation retention capacity are important factors that also determine soil and crop productivity.

Soil carbon and hence productivity is not permanent but may change rapidly depending on land use type and management (Zerihun 2017; Waddington et al.

2010; Reynolds et al. 2015). Much of the literature (Burras et al. 2001; Sa et al. 2001; Batlle-Aguilar et al. 2011) indicates that the conversion of forest to agriculture and other forms of land use such as plantations and woodlots is the major cause of soil productivity decline in the tropics. Brams (1971) showed a 50% reduction in the *SOC*, only 5 years after forest clearing in Sierra Leone.

Residue management methods employed in agriculture also lead to changes in *SOC*. Adiku et al. (2009) showed in Ghana that where crop residues were removed (e.g., by burning, or cutting to feed animals with no return of manure), the *SOC* declined rapidly from the long-term fallow land value of 18 g kg^{-1} to 7 g kg^{-1} with 4 years of maize cropping. However, where the residues were maintained as mulch, the rate of *SOC* decline was much slower, from 18 g kg^{-1} to 15 g kg^{-1} over years. A greater buildup of SOC in forests than other land use types would be expected because of long-term continuous litter addition (Brinson et al. 1980), for example, by avoidance of cultivation losses and reduced decomposition due to lower temperatures under a tree canopy. For croplands, the constant disturbance of the soil enhances *SOC* decomposition (Lal 1997; Hulugalle et al. 1984; Kang 1993; Dalal et al. 1991), and the constant harvest or removal of plant organic material (Feller 1993) would increase the *SOC* loss due to the partial exposure of the soil to high temperatures during off-seasons.

Despite these findings, the manner in which land use types affect soil carbon storage in different ecological zones is not well understood. The question of interest here is whether a given land use type will equally impact soil properties in different rainfall and vegetation zones. In other words, can we generalize that cropping will adversely affect soil productivity irrespective of the carbon input capacity of different ecological zones? This aspect of research is still lacking in Ghana, even though it has relevance for the design and management of soil productivity. The focus of this chapter is to examine how four land use types (forest, woodlot/plantation, cassava cropping, and maize cropping) affect soil carbon content and other properties at six farming sites of Ghana (across two ecological zones).

Materials and Methods

Sites

Six (6) farming sites from two agro-ecological zones, all in southern Ghana, were selected for this study (Fig. 1). Three of the farming sites (Accra Metropolis, Ga East District, Ga West District) fall in the coastal savanna zone of Ghana and receives 650–1000 mm rainfall. Though the vegetation is largely grassland, some derived savanna locations still host original pockets of forestland. The dominant soil type of the Greater Accra Region based on FAO/UNESCO classification is Ferric Acrisol and Umbic Leptosol (Soil Research Institute 1999). The remaining three sites (Yilo Krobo District, Shai Osudoku District, and Upper Manya District) fall within the forest-savanna transition zone (hereinafter transition zone) receiving 1500–2000 mm rainfall. Vegetation is largely forest at some portions and mixed with grassland in other portions. The soils of the transition comprise Cambic Arenosol and Calcic

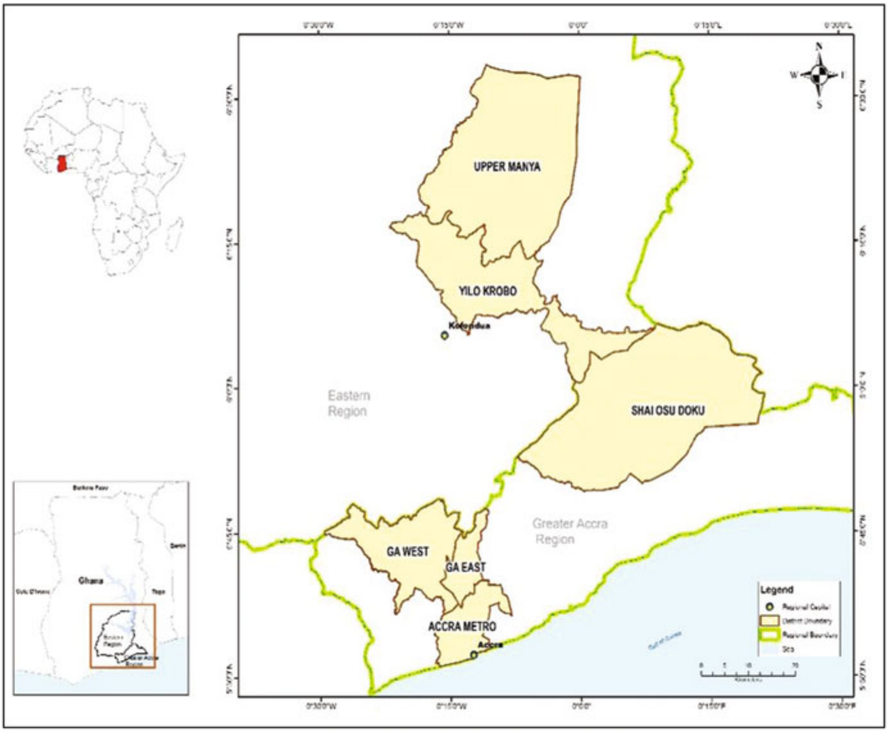

Fig. 1 Map shows position of Ghana in West Africa (top left), the location of the study sites in southern Ghana (bottom left), and the details of the districts (Ga West, Ga East, Accra Metropolis, Yilo Krobo, Shai Osudoku, and Upper Manya) used in Ghana

vertisol. Rainfall in both ecological zones is bimodally distributed, with a major wet season from March to July and a minor wet season from September to November. Agriculture is the main source of livelihood at all the sites.

The first site (Accra Metropolis) in the coastal savanna zone was located at the University of Ghana Farm and hosts a forest of more than 150 years old. Nearby the forest is cleared area which has been cropped to maize (*Zea mays*) and cassava (*Manihot esculenta*) for more than 20 years by University Farm workers. The maize fields receive periodically modest fertilizer application of not more than 30 kg N ha^{-1}. Also, located at the University Farm is an 18-year-old woodlot of *Leucaena species* established on a previously cropped land. Experimental plots at the University Farm were not included in this study. The soils under the forests and woodlots have little mechanical disturbance for many years, but the croplands are plowed and cultivated annually. The second site in this zone (Abokobi) also carried a 70-year-old forest with adjacent lands cropped to maize and cassava for not more than 10 years. A plantation of plantain (*Musa* spp.) was established near the forest. The third site (Pokuase) carried a forest of more than 70 years, an oil palm (*Elaeis guineensis*) plantation as well as cassava and maize farms.

The fourth site (Yilo Krobo), which is located in the transition zone carried a forest of more than 50 years, an oil palm plantation and relatively young crop farms of maize and cassava. The fifth site (Shai Osudoku) holds a protected forest with mature trees of more than 100 years old. For this reason, soil sampling was restricted to the fringes of the forest. Other land use systems at this site include an 18-year mango (*Mangifera indica*) plantation, maize, and cassava farms. The sixth site (Upper Manya) has a forest of more than 50 years old, along with oil palm plantations, and recent arable farms.

Table 1 Land use types at the two agroecological zones

Site	Ecology	Rainfall (mm)	Dominant soil	Land use	Age (years)
Accra-Metropolis	Coastal savannah	700	Ferric Acrisol	Maize	10
				Cassava	10
				Woodlot	20
				Forest	>150
Ga-East	Coastal savannah	800	Ferric Acrisol	Maize	5
				Cassava	8
				Plantation	6
				Forest	>70
Ga-West	Coastal savannah	800	Umbic Leptosol	Maize	4
				Cassava	10
				Plantation	10
				Forest	>70
Yilo Krobo	Forest savannah	900–;1500	Calcic Vertisol	Maize	10
				Cassava	8
				Plantation	23
				Forest	>60
Shai-Osudoku	Forest savannah	900–1500		Maize	>50
				Cassava	>50
				Plantation	18
				Forest	>100
Upper-Manya	Forest savannah	900–1500	Cambic Arenosol	Maize	5
				Cassava	7
				Plantation	10
				Forest	>50

Farmers' best estimates

Sampling and Analysis

For this study, four land use types, namely, maize cropping, cassava cropping, plantations (teak, mango, plantain, oil palm, woodlot), and natural forests were selected (Table 1). Fifty-four (54) farms across the six sites were selected and visited from April to May 2017, and soils were sampled from each land use type from the depth of 0–20. The cropping history of the 54 farms were documented during a prior survey by Owoade et al. (2017). At each site, at least three maize and three cassava farms were sampled in triplicates and bulked to obtain a composite sample for each farm. In addition, soils were sampled from the plantations and the natural forests.

The disturbed top soil (0–20 cm) and separately sampled undisturbed soil cores were brought to the laboratory for analysis. The bulk density was determined on the soil cores. Disturbed soils were air-dried, crushed, and sieved through 2-mm sieve for the determination of texture, total soil carbon, pH, total nitrogen, available phosphorus, and exchangeable cations (K, Mg, Ca, Na). Exchangeable bases were determined by extraction with 250 ml of buffered 1.0 M ammonium acetate followed by flame photometric determination and the effective cation exchange capacity (ECEC) was determined as the sum of exchangeable cations. Soil texture determination followed the procedure of Bouyoucous (1951) as modified by Day (1965) using sodium hexametaphosphate as the dispersant. Soil pH was determined in 1:1 soil to water ratio using a MV88 Praitronic pH meter and electrode. Available phosphorus (AvP) was determined colorimetrically after extraction with Bray 1 solution (Bray and Kurtz 1945) and the concentration measured using a UV-Spectrophotometer. Total soil carbon and nitrogen were determined using TruMac Carbon, Nitrogen, and Sulfur analyzer (Model N1914).

The soil carbon content was converted to stocks (C_{st}) using:

$$C_{st} = A \times \rho_b \times z \times SOC \tag{1}$$

where A is the land area (1 ha = 10^4 m^2), ρ_b is the soil bulk density (kg/m^3), and z is the soil depth (0.20 m).

Statistical Analysis

Analysis of variance was conducted using MINITAB software to determine the influence of land use types and site location on soil properties.

Table 2 Variation of soil properties with sites

Site	Ecology	Bulk density (g/cm^3)	SOC (g/kg)	pH	Avail P (mg/kg)	N (mg/kg)	ECEC (cmol/kg)
Accra Metropolis	Coastal savanna	1.27 ± 0.16	12.4 ± 6.0	4.4 ± 0.4	18.7 ± 12	4.3 ± 0.4	3.11 ± 0.86
Ga East		1.38 ± 0.10	11.49 ± 5.0	5.05 ± 0.5	10.9 ± 6.0	4.1 ± 0.3	3.06 ± 0.91
Ga West		1.29 ± 0.14	15.6 ± 8.6	5.6 ± 0.54	10.8 ± 6.1	1.90 ± 0.9	4.12 ± 1.4
Yilo Krobo	Transition	1.19 ± 0.15	23.50 ± 6.5	6.15 ± 0.54	15.70 ± 4.3	1.20 ± 0.6	6.79 ± 2.16
Shai Osudoku		1.32 ± 0.07	18.20 ± 5.8	6.15 ± 0.39	12.90 ± 7.1	3.6 ± 2.2	6.64 ± 1.52
Upper Manya		1.29 ± 0.08	13.10 ± 2.7	6.03 ± 0.0.48	7.90 ± 4.2	1.80 ± 0.23	4.29 ± 1.5
p-value		0.007	0.000	0.000	0.008	0.000	0.000

Results and Discussions

Effect of Site Locations on Soil Properties

There were significant differences among some soil properties at the various sites (Table 2). For example, soil texture, expressed as clay ratio (sand + silt)/clay), differed significantly with site, with high values (>11) at sites 1, 2, 5, and 6, and low values (4–5) at locations 3 and 4 (not shown). The bulk density differed significantly with site ($p = 0.007$) with higher values observed for the coastal savanna zone (1.3–1.4 g/cm^3) than in the transition zone (1.2–1.3 g/cm^3). The *SOC* also differed significantly with site ($p = 0.000$), with higher values in the transition zone (1.3–2.4 g/kg) than the coastal savanna zone (1.2–1.6 g/kg). Apparently, the higher *SOC* of the transition zone could be attributed to a greater carbon input by the high rainfall and more forest vegetation than the savanna ecological zone. The higher SOC of the transition zone may explain, the lower bulk density values, as these two properties are inversely related.

The pH differed significantly ($p = 0.000$) between ecological zones with the transition zone having higher values (6.0–6.2) than the coastal savanna (4.4–5.6). Soil pH differences may have consequences to crop performance because most nutrient elements are usually available in the pH range of 5.5–6.5 (Motsara and Roy 2008). The available P was significantly different ($p = 0.008$) among the sites. Though site 1 (Accra Metropolis) in the coastal savanna zone had the highest value (18.7 mg/kg), and the variability was also very high (SD = 12 mg/kg). Except for the site 6 (Upper Manya) which had the lowest available P (7.9 mg/kg), the average P values were quite similar for the two ecological zones; 11–18 mg/kg for the coastal savanna and 8–16 mg/kg for the transition zone. In general, the available P levels were somewhat adequate for plant growth, given a threshold of 11 mg/kg (Adeoye and Agboola 1985). Total nitrogen values varied significantly with site ($p = 0.000$) with higher values for the coastal savanna (1.1–4.3 mg/kg) than the transition zone (1.2–3.6 mg/kg). Though the ECEC can be considered as generally low but differed significantly ($p = 0.000$) between ecological zones, with the transition zone having 4.3–6.8 cmol/kg and the coastal savanna having 3.1–4.1 cmol/kg. Based on the soil property values, it may be concluded that the transition zone provided a much better soil condition for cropping than the coastal savanna zone.

Not all the soil properties were significantly affected by land use type. Across all sites, land use type had significant ($p = 0.003$) effect on the *SOC*, with a clear-cut difference between the *SOC* of the forest (21 g/kg) and the rest of the land use types where the *SOC* ranged from 13.0 (maize) to 14.0 (woodlot/plantation) g/kg (Table 3). Land use type also had significant effect ($p = 0.000$) on the bulk density, with the forests having the lowest value (1.2 g/cm^3) and maize farms having the highest (1.34 g/cm^3). There were no significant effects of land use types on available P, N, ECEC, or pH.

The interactive effects between sites and land use type were only significant for the *SOC* and bulk density. Incidentally, these two properties are the major determinants of the total carbon stock (Eq. 1). Land use type significantly ($p = 0.013$) affected the total carbon stocks at the various sites in the order: forest > plantation > cassava > maize. Across the sites, the forest soils had the highest average storage of 48,216 ± 12,811 kg/

Table 3 Variation of soil properties with land use types

Land use	Bulk density (g/cm^3)	SOC (g/kg)	pH	Avail P (mg/kg)	N (mg/kg)	ECEC (cmol/kg)
Maize	1.34 ± 0.15	13.0 ± 7.40	5.6 ± 0.79	14.8 ± 7.7	2.50 ± 1.3	4.60 ± 0.1.6
Cassava	1.29 ± 0.08	15.00 ± 6.4	5.70 ± 0.82	11.61 ± 7.0	2.90 ± 1.4	4.60 ± 2.4
Plantation	1.32 ± 0.14	14.0 ± 5.90	5.60 ± 0.82	11.80 ± 6.3	3.00 ± 1.3	4.40 ± 1.7
Forest	1.20 ± 0.10	20.9 ± 6.9	5.30 ± 0.71	13.10 ± 10	2.70 ± 2.3	5.10 ± 2.5
p-value	0.005	0.003	NS	NS	NS	NS

Table 4 Land use effects on soil carbon stocks

Region	Land use	Carbon stock (kg/ha)	% Forest carbon
Coastal savanna			
	Maize	24,316 ± 12,155	48
	Cassava	27,671 ± 10,839	54
	Woodlot	30,325 ± 4450	60
	Forest	50,491 ± 12,755	–
Forest-savanna transition			
	Maize	41,897 ± 12,263	88
	Cassava	43,001 ± 10,007	91
	Plantation	45,019 ± 14,786	95
	Forest	47,382 ± 20,252	–

ha "..(not shown) 4" followed by plantations (36,774 ± 14,482 kg/ha), cassava (35,007 ± 14,014 kg/ha), and maize (33,905 ± 12,811 kg/ha). Other studies (Djagbletey et al. 2018) have also reported higher soil carbon stocks for denser forests in the Guinean savanna zone of Ghana. In other works, carbon stocks as high as 59,450 kg/ha determined for forest soils in the semi-deciduous forest zone of Ghana by Dawoe (2009).

With regard to ecological zones, the results showed that the differences in land use impact on soil carbon in the transition zone was smaller than in the coastal savanna zone (Table 4). In the coastal savanna zone, maize accrued 48% of the forest carbon stock, while the cassava and plantation accrued 54% and 60%, respectively, suggesting that the plantations were most effective in soil carbon restoration. With regard to the transition zone, however, the soil carbon restoration effectiveness was generally high 90–95% for all the land use types. Though the plantations impact was again the highest, values above 90% accretion generally suggests that all the land use types were equally effective.

Options for *SOC* accretion must consider the differential effects of land use types as well as ecological zones. Our observations indicated that cropping of the land depleted the *SOC* the most. The reduction of *SOC* stocks on cropped lands can be attributed to factors such as the harvest removal of plant organic matter (Feller 1993), constant disturbance of the soil that enhances decomposition (Lal 1999; Hulugalle et al. 1984; Kang 1993; Dalal et al. 1991), and the partial exposure of soil to high temperatures during off-seasons when vegetation cover is reduced. These researchers (Yilfru and Taye 2011; Caravaca et al. 2002; Malo et al. 2005) also recorded greater SOC in forest compared to cultivated land. Though our sampling did not include intercropping systems, the observation that cassava cropping accrued high carbon stock than maize suggests that a maize-cassava intercropping could, perhaps, maintain a higher carbon addition, because of the longer life cycle of cassava and higher SOC accretion than maize.

The plantation land use type showed a higher SOC accretion but would require relatively long periods of time to achieve, thus preventing cropping of the lands for some time. Presumably, a combination of plantation and cropping is desired to ensure both crop productivity as well as *SOC* maintenance. This can be accomplished by agroforestry, which has been promoted in many parts of the tropics to enhance crop yields (Kang 1993), but the adoption rates have continued to be very low. Apparently, the competition between live trees and crops for resources in agroforestry systems can reduce crop productivity (Ong et al. 1991), thereby handicapping the adoption of the system by farmers. Tree-crop rotations, as practiced under the traditional shifting cultivation, could also be an effective alternative to agroforestry. The tree phase of the rotation would permit the rebuild of the *SOC* which is depleted during the cropping phase. This traditional shifting cultivation needs to be further researched for its role in soil carbon management and crop production.

Conclusion

Soil productivity in Ghana is influenced by both land use type and agro-ecological zone. Findings from this study indicated that soil productivity conditions for agriculture were less favorable for agriculture in the coaster savanna than the forest-savanna transition zone. Furthermore, land use types had significant impact on the carbon storage, with maize-based cropping systems having the lowest carbon stocks. Woodlot/plantation types of land use restored the SOC and productivity more effectively than croplands. In effect, the effectiveness of land use systems for soil productivity maintenance differs with agro-ecological zones. This must be factored into the design of land management measures.

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