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Full Length Research Paper

Soil Property Degradation Trends in Ultisols of Nigeria's Semi-Humid Regions

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Better understanding of how soils respond to land use is needed to enable science-based land management interventions. The present study investigated the relative changes in properties of ultisol under conventional tillage for arable crops and compared with fallowed plot (greater than 10 years of continuous no-till fallow) in the semi-humid Nsukka of southeastern Nigeria. Soil samples were collected from designated profile horizons for determination of soil properties. In cultivated plot relative to fallowed plot, soil erodibility increased by 2.5% (Ei + 0.11), total porosity decreased by 1.1%, whereas macro- and microporosity increased by 3.4 and 7.1%, respectively. Soil saturated hydraulic conductivity increased by 4.9%. The degree of topsoil saturation with water was similar in both the cultivated and the fallowed plots. Soil pH increased (7%) when exchangeable acidity increased (21.3%, +0.46 cmol (+) kg^{-1}). Losses of organic carbon (28%, -2.58 gkg^{-1}), total N (26%, -0.17 gkg^{-1}), available P (47%, -2.63 $mgkg^{-1}$), Ca (55%, -1.75 cmol (+) kg^{-1}), CEC (17%, -1.11 cmol (+) kg^{-1}), and base saturation (11.3 %) due to cultivation were observed. Since the fallowed plot that was previously under cultivation was able to show more favourable values of the measured soil properties than the cultivated plot without human activity, the study deduces that an ultisol can be resilient.

Key words: Ultisol, land use system, soil property, semi-humid, Nigeria.

INTRODUCTION

Environmental degradation caused by unsuitable land use is a worldwide problem. Soil's capacity to carry out its functions of biological production, environmental protection and human health sustenance is impaired due to climate effects and anthropogenic disturbances (Hertmink et al., 2008).

Land use profoundly influences the functionality of the three facets of soil properties: Physical, chemical and biological in terms of relative changes at multiple levels of the agro-ecosystem. Soil properties that can be changed in a short time by land use are dynamic soil quality indicators (Sanchez- Maranon et al., 2002), while an assessment of dynamic soil quality indicators influenced by land use requires four approaches to avoid misuse of soil quality paradigm and include: (i) Separation of soil environments with narrow climate and soil ranges; (ii) Identification of native and current soil properties within an environment; (iii) Description of the relative quantified

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changes of individual soil properties, and (iv) Inference of the state of individual soil functions.

Spatial variability in soils exists at many scales with different dominant controlling factors. An understanding of the variability and distribution of soil nutrients as influenced by site characteristics (controlling factors) including climate, landscape features, and land use is critical for assessing the future of land use change in soil nutrients (Kosmas et al., 2000;). Also, the direction and degree of soil quality changes in managed ecosystems depend on these factors.

Soil-landscape relationships result from short and long-term pedogeomorphic processes. Parent material, climate, and geological history are major factors affecting the distribution of soil properties at continental scale (Akamigbo and Asadu, 1983), whereas land use, land use history, and topography are the dominant controls at smaller scales such as catchment scale (Fu et al., 2000). Furthermore, land use influences soil property variations since land use and soil management practices influence such processes as erosion, oxidation, mineralization and soil nutrient leaching.

In field experiments, Wei et al. (2010 found that land use conversions resulted in significant soil degradation through loss of fine soil particles, soil organic carbon (SOC), and nutrients. However, after 28 years of afforestation of grassland, SOC and STN increased. This study suggests that land use changes affect soil properties and soil quality indicators.

A key feature of soils is profound variation in their properties and may differ among soil profile horizons due to the transport and storage of water and nutrients across and within the soil profile. Both horizontal and vertical variability of soil properties have been studied in temperate soils (Schilling et al., 2009) when compared to little work and literature availability on the variability of Nigerian soils (Oku et al., 2010).

Nutrient and water uptake are not always the same at different soil depths because of soil-forming factors that affect different properties differently at different depths (Cassel, 1983). Limited studies on vertical soil variability (Oku et al., 2010) show soil pH to increase with depth and least variable, irrespective of depth. They also found variability of soil organic matter, total N, available phosphorus and CEC to increase with depth and ranged between moderate and high.

An important question is to what extent are soil properties different along profile depths in the different land uses of the study sites. Understanding the vertical distribution of soil properties along profile depths could help to predict the proneness of such soils to erosive influence. Knowledge of their variability is essential in applying location-specific land management interventions. The objective of this study was to quantify and compare soil properties of 4-year conventionally and continuously tilled arable cropland with those of an adjacent native site of greater than 10 years of continuous no-till fallowed sites in the semi-humid zone of Nsukka, Nigeria.

MATERIALS AND METHODS

Features of the study location

The study was conducted on an ultisol of Nsukka (06° 52' N; 07° 24' E), Nigeria on an altitude of 400 m above sea level (m asl). Its climate is characteristically sub-humid tropical, with mean annual total rainfall of about 1600 mm; of which distribution is bimodal, with peaks during July and October in the first and second phases, respectively. Mean minimum temperature is 21.8°C and relative humidity ranges between 70 and 80% (Oko-Ibom and Asiegbu, 2006). The soil of the study location is an utisol characterized as low activity clays (Ezeaku, 2006). The soil is well drained, prone to erosion and leaching losses of nutrients, hence of low fertility status. The vegetation is characteristically derived savanna (Savanna-mosaic) agroecology, which represents different land uses such as forest, secondary forest, cultivated areas, and grazed grass pasture in a soil-landscape system.

Two profile pits were dug on a 4-year conventionally and continuously tilled arable cropland system and another two sited on a plot under 10-year natural fallow system. The two land uses were 500 m apart, while the distance between the two profiles was 530 m apart. Profile samples were collected at different soil horizons (0-20, 20-45, 45-70, 70-100 m) for the first pit on a 4-year arable cropland) using cores of 0.050 m in diameter and 0.051 m in height. The method of sampling was discrete, which involved collecting samples at designated soil profile horizons (Muller and McBratney, 2001). Horizon depths for soil sampling among the different profile pits vary. However, soil horizon samples on each system were bulked and air-dried, crumbled and sieved through a 2-mm screen.

The analytical characteristics of the soil horizon samples were determined in the following manner. Particle-size distribution was determined by the pipette method (Gee and Bauder, 1986), soil bulk density as described by Blake and Hartge (1986), while porosity was calculated as a function of the total volume not occupied by soil solids, assuming a particle density of 2.65 gcm^{-3} and mathematically expressed as follows:

$$f = 1 - Bd^{-}/Pd \times 100\ \% \quad (1)$$

Where f = total porosity (%), Bd = bulk density (gcm^{-3}), Pd = particle density assumed (2.65 gcm^{-3})

Erodibility index of the soil was calculated as a ratio of sand + silt to clay (Hudson and Vooorees, 1995). Soil saturated hydraulic conductivity (Ks) was determined based on Klute and Dirksen (1986) method and calculated by using the transposed Darcy's equation for vertical flows of liquids:

$$Ks = (Q/At)/(L/DH \quad (2)$$

Where, Ks = saturated hydraulic conductivity (cm h^{-1}), Q = steady-state volume of water outflow from the entire soil column (cm^3), A = the cross-sectional area (cm^2), t = the time interval (h), L = length of the sample (cm), and DH = change in the hydraulic head (cm).

Soil pH was determined using 1:2.5 soil water suspension (adequate to wet the glass electrode) and read off using pH meter (McLean, 1982). Organic carbon was obtained by the wet dichromate acid oxidation method (Nelson and Sommers, 1982). Total nitrogen was determined using the Micro-kjeldhal method (Bremmer and Mulvaney, 1982), while available phosphorus was assayed by Bray P-2 bicarbonate extraction method (Olson and Sommers, 1982). Exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were extracted in 1 N NH_4OAc buffered at pH 7.0. Exchangeable

Table 1. Variation in soil physical properties in relation to soil depth (cm) of cultivated land.

Hz	Depth (cm)	Sand	Silt	Clay	Tx	Si/Clay	Ei	Bd Mgm^{-3}	Tp	Ma.p	Me.p	Mi.p	Ks cm h^{-1}	Sa cm^3/cm^3
		(%)							(%)					
Ap	0-32	74.2	7.4	18.4	Sl	0.40	4.43	1.35	49.1	23.7	13.3	12.1	0.82	0.44
AB	33-65	70.3	9.9	19.8	Sl	0.50	4.03	1.37	48.3	21.4	10.2	16.7	0.70	0.45
Bt_1	66-99	55.7	12.5	31.8	Scl	0.39	2.14	1.47	44.5	17.8	6.4	20.3	0.24	0.48
Bt_2	100^+	54.2	10.9	34.9	Scl	0.31	1.87	1.49	43.7	14.0	6.2	23.5	0.19	0.49
Mean		63.6	10.2	26.23		0.40	3.12	1.42	46.4	19.2	9.0	18.2	0.46	0.46
SD		10.1328	2.1376	8.3436		0.0778	1.2996	0.0702	2.6957	4.2461	3.3925	4.8973	0.3191	0.0238
CV (%)		16	21	32		20	42	5	6	22	38	27	66	5

Tx= texture, Si= silt, Ei= erosion index, Bd= bulk density, Tp= total porosity, Ma.p= macro porosity, Me.p= meso porosity, Mi.p= micro porosity, Ks= saturated hydraulic conductivity, Sa= degree of saturation. CV= coefficient of variability.

Table 2. Variation in soil physical properties in relation to soil depth (cm) of fallow land.

Hz	Depth (cm)	Sand	Silt	Clay	Tx	Si/Clay	Ei	Bd Mgm^{-3}	Tp	Ma.p	Me.p	Mi.p	Ks cm h^{-1}	Sa cm^3/cm^3
			(%)							(%)				
Ap	0-30	72.6	8.6	18.8	Sl	0.45	4.32	1.37	48.3	24.2	7.8	16.3	0.78	0.44
AB	31-82	70.0	10.1	18.9	Sl	0.54	4.23	1.40	45.3	20.3	7.9	17.1	0.78	0.44
Bt_1	83-135	66.4	12.5	29.6	Scl	0.42	2.66	1.47	44.5	12.6	11.7	20.2	0.25	0.47
Bt_2	135^+	54.8	10.9	32.1	Scl	0.34	2.05	1.48	44.2	13.0	8.5	22.7	0.23	0.48
Mean		65.9	10.5	24.9		0.44	3.32	1.43	45.6	17.5	8.98	19.0	0.51	0.46
SD		7.856	1.626	7.003		0.083	1.137	0.054	1.875	5.686	1.843	2.944	0.312	0.021
CV (%)		12	15	28		19	34	3	4	32	21	15	61	5

Tx= texture, Si= silt, Ei= erosion index, Bd= bulk density, Tp= total porosity, Ma.p= macro porosity, Me.p= meso porosity, Mi.p= micro porosity, Ks= saturated hydraulic conductivity, Sa= degree of saturation. CV= coefficient of variability.

acidity (EA) was determined by titration with 0.05 N NaOH, while CEC was determined titrimetically using 0.01 N NaOH.

Statistical analysis

All data were statistically analyzed using Genstat 9.2 Edition. A *t*-test was used to verify whether there were statistically significant differences. Changes in soil properties can be used to determine whether soil quality, from environmental viewpoint, is improving, stable, or declining with changes in land use (Brejda et al., 2000). Soil variability was estimated using mean and coefficient of variation (CV). Soil properties with larger CV values are more variable than those with smaller CV values. Ranking of variability was done using the classification scheme by Wilding (1985) as follows:

Little variation (CV = < 0-15%)
Moderate variation (CV = 16-35%
High variation (CV = > 36%)

RESULTS AND DISCUSSION

Variability in soil properties

Representative soil profiles showing some properties of the fallowed and the cultivated land uses were studied. The physical and chemical properties of the soils are shown in a horizon sequence A-Bt_2 (Tables 1 to 4). Tables 1 and 2 present the physical properties of the soil profiles.

Table 3. Variation in soil chemical properties in relation to soil depth (cm) of cultivated land.

Hz	Depth (cm)	pH H_2O	OC	TN	Av. P	Ca	Mg	Na	K	EA	CEC	BS
			gkg^{-1}		Mgkg^{-1}			cmol kg^{-1}				%
Ap	0-30	5.11	9.12	0.65	5.63	3.18	1.30	0.03	0.07	2.16	6.40	43.22
AB	31-82	5.04	10.80	0.71	6.40	2.60	1.80	0.02	0.13	3.28	7.24	52.01
Bt_1	83-135	4.71	14.10	0.87	7.12	2.30	1.85	0.06	0.18	3.42	8.10	55.86
Bt_2	135^+	4.68	14.92	0.93	8.36	2.14	2.24	0.08	0.24	4.06	9.27	60.11
Mean		4.89	12.24	0.79	6.88	2.56	1.79	0.05	0.16	3.23	7.75	52.80
SD		0.222	2.739	0.1317	1.161	0.458	0.3856	0.0275	0.0723	0.7900	1.2268	7.193
CV(%)		5	22	17	17	18	22	58	47	25	16	14

OC= organic carbon, TN= total nitrogen, Av.P= available phosphorus, Ca= calcium, Mg= magnesium, Na= sodium, K= potassium, EA= exchangeable acidity, ECEC= effective cation exchange capacity, BS= base saturation percentage. CV= coefficient of variability.

Soil texture ranged between sandy loam and sandy clay loam. Sand fraction was predominant in relation to the other size fractions in the study site. The predominance of sandy loam is an indication of the uniformity of the site in lithological origin, being false- bedded sandstone of the cretaceous sediment (Akamigbo and Asadu, 1983).

In both land uses studied, the trend in sand and clay movement with depth was irregular. In the topsoil (0-32 cm) of the cultivated soil relative to reference (native) soil, sand had the least variation, while silt and clay varied moderately (CV >16,<35%). Percentage clay content (18.4 %) was less in the upper surface layer as compared with 34.9% obtained in the lower (100^+ cm) soil depths, indicating that clay increased with depth, perhaps due to the pedogenetic process of illuviation. Silt/clay ratio varied between 0.31 and 0.50 (mean = 0.40; CV = 19.5 %) in the cultivated soil and from 0.34 to 0.54 (CV = 18.9 %) in the fallowed soil (Tables 1 and 2). Mean silt/clay ratio was less than unity, signifying low weatherability of the soil and pedogenesis under the land uses.

In terms of soil degradation, soil erodibility at the soil surface increased by 2.5% (Ei + 0.11) in cultivated soil (Table 1) relative to native soil (Table 2). However, the variability of degradation index for both soils is generally high (> 36 %) (Wilding, 1985).

Other properties of the soils such as bulk density, porosity, saturated hydraulic conductivity (Tables 1 and 2) varied. Bulk density increased (1.63%) with depth. In the cultivated site minimum bulk density (1.35 Mgm^{-3}) occurred at the 0-30 cm depth (which is more or less the plough depth), suggesting pulverization of the surface soils during tillage. Urioste et al. (2006) and Hertmink et al. (2008) also associated low soil bulk density to cultivation; which destroys organo-mineral complexes and the release of soil organic matter and nitrogen, when exposed to oxidation. Channeling and loosing effect of roots could have caused lower bulk density values obtained in the topsoil of the two land uses. The values were all below the critical minimum value (1.5 Mg m^{-3}) (Aune and Lal, 1997). Situations of soil bulk density values above this critical value are capable of impeding crop root growth and development, thereby reducing crop yields.

The distributions of bulk density, Ks and porosity with depth in the two sites are shown in Tables 1 and 2. Some workers have indicated that Ks is affected more by the proportion of the water-conducting pores (macro- and mesopores) relative to that of the micropores (Mbagwu, 1995). The report further showed that high bulk density reduced *Ks,* by decreasing drainable porosity through compaction at the soil surface and consolidation in the subsoil.

In the cultivated and native sites, the distribution of the macro, meso + microporosity varied with soil depth. While saturated hydraulic conductivity and macroporosity decreased, microporosity increased with depth. When compared to the fallow site, the value of microporosity decreased by 34.7% in cultivated land use (Table 1). This observation accords earlier reports (Mbagwu et al., 1983; Oku et al 2010) for some soils in southern Nigeria.

Macroporosity and bulk density are the two important physical properties influencing the Ks of soils. As bulk densities increased to 1.49 Mg m^{-3}; Ks decreased to 0.19 cm hr $^{-1}$ (Table 1). High Ks values found on surface soils could be associated to abundant biopores, textures coarser than loamy fine sand and strong, fine to medium blocky structures in the surface soil (Fu et al., 2000; Mbagwu, 1995).

On the other hand, low Ks on the sub surface suggests low water transmission rate due to clay accumulation and siltation of the pedogenic horizons. Thus, micro-aggregates could have blocked and reduced the number of available pores open for hydraulic flow. This corresponds to increases in clay contents and microporosity as well as higher degree of water saturation as observed in the subsoils of the study sites.

For these test sites, variation was observed with the hydraulic property (Ks) than with porosity and bulk density (Tables 1 and 2). Other investigators, for example Ahuja et al. (1989) and Franzmeier (1991), also reported more variability in Ks than in the total porosity.

The results in Table 3 show that soil acidity (pH)

Table 4. Variation of soil chemical properties in relation to soil depth (cm) of fallow land.

Hz	Depth (cm)	pH H_2O	OC *gkg⁻¹*	TN	Av.P Mgkg^{-1}	Ca	Mg	Na	K	EA	CEC	BS %
						cmol kg^{-1}						
Ap	0-30	5.47	11.70	0.82	8.26	4.93	1.81	0.06	0.09	1.70	7.51	48.12
AB	31-82	5.22	13.54	0.86	10.80	4.20	2.16	0.09	0.16	2.16	9.51	58.31
Bt_1	83-135	5.00	17.20	0.94	16.00	3.40	3.03	0.10	0.26	3.20	12.14.	61.50
Bt_2	135^+	4.93	18.05	0.98	18.30	3.22	2.70	0.12	0.25	3.30	12.30	64.20
Mean		5.16	15.12	0.90	13.34	3.94	2.43	0.09	0.19	2.59	9.77	58.03
SD		0.244	3.006	0.0730	4.616	0.787	0.5447	0.0250	0.8042	0.7859	2.406	7.033
CV(%)		5	20	8	35	20	23	27	42	30	25	12

OC= organic carbon, TN= total nitrogen, Av.P= available phosphorus, Ca= calcium, Mg= magnesium, Na= sodium, K= potassium, EA= exchangeable acidity, ECEC= effective cation exchange capacity, BS= base saturation percentage. CV= coefficient of variability.

increased (7 %) when exchange acidity increased (21.3%, + 0.46 cmolkg^{-1}) in cultivated soil. Spark (1995) made similar observation.

Amounts of soil organic carbon (SOC) found in both soils showed an increase with depth. The decrease on the surface (0-32 cm) of cultivated soil was 28% (-2.58 gkg^{-1}) and accumulated by 63.0% at 100+ cm soil depth (Table 3). Frequent erosion phenomena and crop harvests could be the cause of low organic carbon in arable (cultivated) soils. Similarly, inversion and pulverization of the soil during tillage makes for accelerated mineralization of exposed organic matter (Connoly, 1998).

Mean SOC was higher by 28.3% under fallow soil in relation to cultivated land use (Table 4). The high SOC could be associated to the ability of the fallow soil to sequester higher quantity of carbon due to their long-term existence with very minimal disturbance, decomposition of plant (litter falls) and animal tissue in the soil thereby releasing soil organic matter. Wei et al (2010) reported that environmental and climatic factors also favor higher level of carbon sequestration in the fallow soils as they are covered by trees and as they are under cover vegetation that reduces extreme climatic elements and thus preserves soil moisture and reduces high thermal fluctuations.

The mean values of most of the chemical properties showed increases with soil depth. However, compared to the control (native) soil, there were decreases in the mean values of total N (26%, -0.17 gkg^{-1}), available P (47%, - 2.63 mgkg^{-1}), Ca^{2+} (55%, -1.75 cmol (+) kg^{-1}), CEC (17%, - 1.11 cmolkg^{-1}), and base saturation (11.3%) observed in cultivated surface soil (0-32 cm) (Table 3). These results are in line with the findings by Urioste et al. (2006) that cultivation affected the distribution of organic carbon, total nitrogen and phosphorus in soils of the semiarid region of Argentinian Pampas.

Soil CEC has been classified as low (< 6 cmol. kg^{-1}), medium (6-12 cmol. kg^{-1}) and high (> 12 cmol. kg^{-1}) for some Nigerian soils (Ezeaku et al., 2012). On the basis of this classification, mean CEC of cultivated and fallow soils was low (6.4 cmolkg^{-1}) and medium (7.51 cmolkg $^{-1}$), respectively. Decrease in CEC suggests decrease in buffering capacity, and is a cause for concern as both land use types with low to medium CEC can be catalogued as unsustainable land use. Low CEC value of tropical soils is due to dominance of kaolinitic clays in the fine earth fraction (Spark, 1995). The CEC generally increases with soil pH, an indication that low CEC obtained under cultivated soils could be accounted for by the low soil pH.

Conclusion

The results revealed that there were variations in some of the measured soil properties in cultivated and fallowed fields. Soil properties under fallow have the highest contents of chemical properties and hence an improved soil fertility. The lower content of some of the measured soil properties observed in the cultivated soil was associated to land use modification when compared to the soil properties under 10 year fallow land use. Restoring vegetative cover is critical to remediate degraded land as in the cultivated land and to achieve its sustainable use. The combination of tillage-mulch practices with cropping systems may have synergistic effects on the soil properties. Therefore, location specific adoption of tillage-mulch-crop combination for the soil is recommended for higher SOC and to decrease risk of soil erosion and productivity decline.

Conflict of Interest

The authors have not declared any conflict of interest.

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