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Soil Mercury Distribution in a Forest-Savanna Mosaic in Relation to Soil Fertility

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Abstract: Morphological, physical and chemical properties of a Forest-Savanna Mosaic in Otamiri watershed in Owerri, Southeastern Nigeria were analysed to determine soil mercury (Hg) distribution as it relates to selected soil fertility parameters. A field work was conducted in 2006 using the transect technique involving 6 minipedons and 6 soil profile pits for surficial Hg estimation and pedological classification, respectively. Results show higher mercury burden (QHg) in 5-25 and 45-50 cm irrespective of vegetal form and physiography. Soil Hg loss at 0-5 cm (-16%) was influenced by the loss of total soil carbon (-15%) at the crest and this trend is similar to other physiographic positions. Total carbon, pH, total nitrogen and effective cation exchange capacity had significant relationship ($p = 0.05$) with Hg. Soils were classified as Inceptisols (USDA Soil Taxonomy) and further pedogenesis may naturally filter Hg menace. More intensive sampling and characterization of soils as well as use of multiple regression tool will increase certainty of predictions.

Key words: Humid tropics, land use, pedogenesis, pollution, topography

INTRODUCTION

The quality of soils determines their capacity to function optimally for any intended use. There is pronounced spatial variability in quality of soils in the humid tropics due to land use (Onweremadu *et al*., 2006). Understanding how nutrient resources vary across landscapes has become the focal point of much ecological research (Benning and Seastedt, 1995). Nutrient availability is an important factor controlling net primary productivity (Seastedt *et al*., 1991), implying that characterizing spatial variability and distribution of nutrients in relation to site characteristics, such as land use and other variables are critical for predicting rates of ecosystems process (Schimel *et al*., 1991; Townsend *et al*., 1995) and assessing the effects on future land use change on nutrients (Kosmas *et al*., 2000; Wang *et al*., 2001). Although the composition of parent materials substantially influences soil properties at regional and continental scales (Kosmas *et al*., 1993), land use is an integrator of several environmental attributes which influences nutrients export (Young *et al*., 1996). Land use combined with management practices influence soil nutrients related to processes, such as erosion, oxidation, mineralization and leaching (Fu *et al*., 1999) and this modifies processes of transport of nutrients (Wang *et al*., 2001). In no cultivated land use type, vegetal cover influences soil organic carbon content (Grigal and Ohmann, 1992) and soil quality declines with cultivation of previously untilled soils (Jaiyeoba, 1995), suggesting that land use and type of vegetation must be taken into account when relating soil nutrients to environmental conditions (Hontoria *et al*., 1999).

Urbanization and the attendant deforestation of peri-urban and satellite towns have drastically altered the original rainforest vegetation leading to critical changes in soil fertility, vegetation and water bodies. Some of these changes include loss in soil fertility and compaction which follows the increase in soil fertility (Tiesen *et al*., 1994). Studies have shown that deforestation leads to the leaching of a neurotoxic heavy metal: mercury (Hg) (Roulet *et al*., 2000; Farella *et al*., 2001). It is well known that soils of Amazon are an important reservoir of Hg due to long history of sediment accumulations (Lechler *et al*., 2000; De Oliverira *et al*., 2001; Fardini and Jardim, 2001). Fostier *et al*. (2000) reported that soil erosion resulting from increased deforestation acts as a source of Hg to aquatic ecosystems and this could be worsened with increased mining of river bank soil (Malm, 1998) and slash and burn practice of land clearing as a diffuse source of Hg (Veiga *et al*., 1994). As accentuated relief and high deforestation rates could lead to the leaching of soil Hg, it becomes necessary to consider vegetal type as it relates to soil quality in terms of Hg distribution. Studies have shown fish contamination by Hg in aquatic habits proximal to highly deforested areas (Lebel *et al*., 1997; Souza Lima *et al*., 2000; Webb *et al*., 2004). Such Hg exposures have negative effects on human health (Brabo *et al*., 2000; Dolbec *et al*., 2000). Again, pasture and crop plants act as vehicles for transferring these heavy metals in the soil into the food chain (Onweremadu *et al*., 2006), implying that plants growing on polluted soils constitute serious health and environmental problems not only because of toxicity to crop plants but also because of the potentially dangerous health effects to man and grazing animals (Ellis and Salt, 2003). It is hypothesized that soil mercury varies given forest-Savanna vegetal types and this affects soil fertility. This study evaluates soil mercury distribution in two vegetal forms that are geographically associated and its effect on selected soil fertility parameters.

MATERIALS AND METHODS

Study Area

This study was conducted in the Otamiri watershed covering about 10,000 km^2 and lying between latitudes $4^0 15^1$ and $7^0 00^1$ N and longitudes $5^0 50^1$ and $9^0 00^1$ E. Soils of the study area are derived from Coastal Plain Sands (Benin formation) of the Oligocene- Miocene geological era. It is within the humid tropics, characterized by an annual rainfall range of 2250-2500 mm. Daily temperatures are generally high with a mean of 27°C in all seasons. Depleted rainforest vegetation dominates the site which has a sloping physiography. The slopes have southwest orientation and run into the Otamiri River in Owerri, Southeastern Nigeria. Part of the study site is characterized by dense cloudy forest while an adjacent lying tract is a typical savanna. Following this, nomads from the northern Nigeria settle with their herds of animals on the savanna, where their animals graze and get fattened before sale to southern consumers. Little arable farming is done on this landscape due to fragility of soil, although population pressure is gradually impacting in it, with municipal solid wastes and wastes from military settlement being disposed in the site. The demographic pressure is currently increasing accelerated erosion in the site.

Field Sampling

Two field sampling was carried out in the months of February and July, 2006. Three sampling points were selected based primarily on land use and proximity to Otamiri River. Both forest and savanna vegetal types were one beside the other to prevent chances of sampling different soils. Dominant plants in the forest included oil palm tree (*Elaeis guineensis*), bitter kola (*Garcinia cola*), oil bean tree (*Pentaclethra macrophyllum*), Gmelina (*Gmelina arborea*), sour sop (*Annona muricata*), locust tree (*Robinia pseudocacia*) while giant star grass (*Cynodon nlemfuensis*), goat weed (*Ageratum conyzoides*), guinea grass (*Panicum maximum*), stubborn grass (*Sida acuta*) and elephant grass (*Pennisetum purpureum*) dominated the savanna patch of the landscape (Table 1). Personal communication with land users in the site shows that the forest is over 45 years while the age of the savanna ranges from 10-30 years.

On each sampling site consisting of forest and savanna, 3 transects (5 m apart) made of 3 points: 5, 50 and 100 m (the observed physiographic boundary) dug to 3 depths (0-5, 20-25, 45-50 cm) were sampled giving a total of 27 soil samples per site and 54 soil samples per zone. These samples

Table 1: Brief description of study site

Sampling point	Proximity to the River (m)	Percent slope F	Percent slope S	Elevation (m)	Forest	Savanna
Crest	1100	9	8	130	Heterogenous relief, tropical evergreen plants dominated by broad leaved plants, Thick humus (2 cm thick) dark brown soils.	Flat, less rugged tops, shrubby with abundant grasses especially eleplant grass (*Pennisetum purpureum*)
Midslope	600	6	7	85	Undulating slope, Tropical evergreen plants, epiphytes, thick humus floor (5 cm), Brown soils.	Undulating, Dominated elephant grass (*Pennisetum purpureum*)
Valley bottom	100	3	2	10	Gentle sloping to almost flat, thick forest with emergents open floor, thick litter floor (7 cm), spongy greyish brown soil.	Dominated by Guinea grass (*Panicum maximum*), setaria (*Seteria anceps*), spear grass (*Imperata cylindrica*),very compact soils.

F = Forest, S = Savanna

represented minipedon sampling meant for the purpose of assessing soil mercury distribution in relation to soil fertility indices. In each vegetation type, three soil profile pits representing 3 physiographic units of the site, namely Crest, Midslope and Valley bottom were dug, described and sampled according to the procedure of FAO (1998) and used for soil classification. Three core samples were collected per horizon, giving a total of 45 core samples for bulk density studies. These soil samples were bagged using black polyethene bags and transported to the laboratory of the Federal University of Technology where they were air-dried, crushed and sieved using 2 mm sieve in readiness for laboratory determinations.

Handheld Global Positioning System (GPS) Receiver (Garmin Ltd., Kansas, USA) was used in measuring distances and heights while Abney level was used in estimating slope in percentage.

Laboratory Determinations

Particle size distribution was determined by hydrometer method (Gee and Or, 2002). Bulk density (Total Density) analysis was done by core method according to the procedure of Grossman and Reinsch (2002). Soil pH was measured potentiometrically in 1:2.5 soil/solution ratio (Hendershot *et al*., 1993). Total carbon and total nitrogen content of soils were estimated by elementary detection (Carlo Erba NA-1500 analyzer) while exchangeable cations were extracted with 0.1 m $BaCl_2$ method (Hendershot *et al*., 1993) and analyzed with atomic absorption spectrophotometer.

Total soil Hg levels were determined with the Cold Vapour Atomic Flourescence (CVAF) technique (Pichet *et al*., 1999). In this method, 280 mg of soil was digested in a 10:1 nitric and hydrochloric and mixture, heated at 120°C and then injected into a spectrophotometer. Soil mercury burdens (QHg) were first calculated for each centimetre of soil with the average Hg concentration and density for each depth (0-5, 20-25 and 45-50 cm). The sum of the 3 intervals (0-5, 5-25 and 25-50 cm) was made to evaluate the QHg for the total 50 cm.

Soil Classification

Field and laboratory data were used to classify studied soils using USDA Soil Taxonomy (Soil Survey Staff, 2003). Results of these classifications were correlated to FAO/UNESCO Legend (FAO, 1998).

Data Analyses

Effects of physiography (crest, midslope and valley bottom), of depth (0-5, 20-25 and 45-50 cm) and of land use (forest and savanna) on fertility parameters were analysed statistically through analysis of variance (ANOVA) (SAS, 2000)

RESULTS AND DISCUSSION

In both land use types, soils are generally deep and sandy. Sandiness decreased downslope in both forested and grassland landscapes. The decrease in sand content was more consistent in soils of savanna landscape. Silt sized fraction increased towards the valley bottom, especially in savanna soils. Similar behaviour was shown by clay- sized fractions at epipedal horizons. Within the pedons and in both landscapes there was no common trend in the distribution of these particle sizes. Generally, sand-sized fractions followed by clay dominated the soils of both sloping Forested and Savanna landscapes. Low silt content is in line with the findings of Igwe *et al*. (1995) and Igwe and Stahr (2004). Dominance of sand-sized particles over other sizes is attributable to parent material and climate of the study area. In both land uses, clay and silt sizes dominated the valley bottom, suggesting that both sizes are easily transported from elevated to depressions. This could be due to the their smaller and lighter nature when compared with heavier sand-sized fractions. The silt and clay sizes were more in valley bottom of Savanna soils, indicating that more runoff occurred in savanna landscape resulting to very silty and clayey soil. Bulk density values were lower in forested landscape (Table 2) when compared with savanna soils (Table 3). Generally BD increased with soil depth (Ezeaku and Anikwe, 2006) towards the river. Total surficial soil carbon was higher in the forested landscape than in savanna soils and followed the same pattern in both landscapes (Table 2 and 3). Soil BD increased as total soil carbon decreased. This result is consistent with the published relationships between BD and organic carbon (Manique and Jones, 1991; Federer *et al*., 1993; Heuscher *et al*., 2005). Higher pH and ECEC values were also found in forested soils as compared to their savanna counterparts. Lower pH resulted in low total carbon values and this agrees with the findings of Stevenson (1994), possibly due to lower activity of organic matter decomposers in acidic soils. Such lower soil carbon is a reflection of low ECEC as soil organic matter rise a storehouse of exchangeable cations. Table 4 shows vertical distribution of Hg in the pedosphere of the study site. Soil Hg increased down stream movement and formed a bulge in within soils in both landscapes. Higher concentrations of Hg were recorded in

Table 2: Characterisation of forested soils of the study (pedon analysis)

Horizon	Depth (cm)	Clay ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Sand ($g\ kg^{-1}$)	BD ($mg\ m^{-3}$)	pH (H_2O)	ECEC ($cmol\ kg^{-1}$)	Total carbon ($g\ kg^{-1}$)
Crest (typic dystrudept)/dystric nitisol								
A	0-5	130	70	800	1.44	4.5	3.1	21.2
Bg1	5-25	200	50	750	1.51	4.3	3.5	7.8
Bg2	25-60	210	60	730	1.52	4.3	6.0	6.3
Bg3	60-98	200	60	740	1.58	4.2	6.9	3.3
BCg	98-170	200	40	760	1.60	4.3	3.9	2.2
Midslope (typic endoquept/dystric fluvisol								
A	0-16	120	60	810	1.40	4.6	2.9	22.8
Bg1	16-50	190	50	760	1.48	4.6	4.5	9.6
Bg2	50-86	180	50	770	1.48	4.5	5.5	6.8
Bg3	86-109	180	40	780	1.51	4.3	5.8	4.0
Bg4	109-180	60	40	900	1.58	4.0	2.8	2.5
Valley bottom (fluventic eutropept/eutric fluvisol)								
A	0-20	180	200	620	1.48	5.6	6.1	18.2
Bg1	20-48	200	200	600	1.52	6.0	7.1	9.2
Bg2	48-80	210	190	600	1.58	6.2	7.8	5.8
Bg3	80-110	200	180	620	1.63	6.5	9.2	5.2
Bg4	110-185	210	170	620	1.68	6.4	7.1	3.6

BD = Bulk Density; ECEC = Effective Cation Exchange Capacity

Table 3: Characterization of savanna soils of the study site (pedon analysis)

Horizon	Depth (cm)	Clay ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Sand ($g\ kg^{-1}$)	BD ($mg\ m^{-3}$)	pH (H_2O)	ECEC ($cmol\ k\ g^{-1}$)	Total carbon ($g\ kg^{-1}$)
Crest/(Typic dystrudepts dystric nitisols								
A	0-7	110	30	860	1.63	4.4	2.6	12.6
Bg_1	3-28	200	50	750	1.64	4.4	3.0	10.0
Bg_2	28-65	200	50	750	1.66	4.5	2.9	5.2
Bg_3	65-102	210	60	730	1.68	4.4	3.3	3.6
BCg	102-185	210	60	730	1.71	4.3	4.2	1.8
Midslope typic endoaqueptDystric fluvisol								
A	0-12	120	40	810	1.65	4.5	2.8	10.2
Bg_1	12-25	200	60	740	1.67	4.1	4.2	8.8
Bg_2	25-63	190	50	760	1.68	4.4	4.8	7.4
Bg_3	63-99	200	60	740	1.69	4.3	5.0	5.1
Bg_4	99-188	210	60	730	1.72	4.5	5.1	3.6
Valley bottom fluventic eutrpept eutric fluvisol								
A	0-20	220	220	560	1.69	4.6	5.6	9.2
Bg_1	22-31	200	210	590	1.70	4.6	5.3	8.2
Bg_2	31-55	190	210	600	1.71	4.7	5.8	6.2
Bg_3	55-90	200	200	600	1.75	4.9	6.2	5.6
Bg_4	90-190	200	200	600	1.78	5.6	6.0	5.1

BD = Bulk Density; ECEC = Effective Cation Exchange Capacity

Table 4: Distribution of soil Hg in the study site

Forest			Savanna		
Horizon	Depth (cm)	Hg ($mg\ kg^{-1}$)	Horizon	Depth (cm)	Hg ($mg\ kg^{-1}$)
Crest					
A	0-5	12.0	A	0-3	1.6
Bg_1	5-25	11.6	Bg_1	3-28	13.8
Bg_2	25-60	9.9	Bg_2	28-65	11.2
Bg_3	60-98	5.2	Bg_3	65-102	10.6
Bcg	98-170	2.6	Bcg	102-185	9.2
Midslope					
A	0-16	15.6	A	0-12	2.2
Bg_1	16-50	13.2	Bg_1	12-25	16.1
Bg_2	50-86	14.8	Bg_2	25-63	15.6
Bg_3	86-109	7.6	Bg_3	63-99	9.8
Bc_4	109-180	2.8	Bc_4	99-188	9.2
Valley bottom					
A	0-20	18.2	A	0-22	5.6
AB	20-48	17.6	AB	22-31	23.2
Bg_1	48-80	6.4	Bg_1	31-55	6.9
Bg_2	80-110	6.2	Bg_2	55-90	5.2
Bg_3	11-185	5.9	Bg_3	90-190	4.9

Table 5: Soil mercury burden (QHg) in the upper 50 cm (mean values) (Minipedon analysis)

Depth (cm)	Crest forest	Savanna	Midslope forest	Savanna	Valley forest	Bottom savanna
0-5	2.6	1.9	2.1	1.0	4.0	4.6
5-25	11.1	8.2	6.1	6.8	15.0	14.2
45-50	10.3	6.1	6.2	7.0	16.1	15.3
0-50	24.0	26.2	14.4	14.8	35.1	34.1

savanna landscape irrespective of physiographic locations. These results indicate that exposure of soils by devegetation and consequent formation of grasslands has promoted soil erosion and leaching of soil Hg.

Minipedon studies indicate that Hg burdens in each zone shows a significant reduction ($p<0.05$) at the epipedons (Table 5). There is significant decrease ($p<0.05$) of Hg in the savanna not only in the surface layer but also in the two zones of 20-25 cm and in only one zone of 45-50 cm (Table 5). At 25-50 cm, the influence of deforestation reduced as only two zones exhibited a significant reduction ($p<0.05$). Table 6 shows the ECEC and TEB (total exchangeable bases) are significantly lower ($p<0.05$) in each of the zones of the savanna soils. The same trend were followed by total carbon and total nitrogen in all the physiographic zones.

Table 6: Difference between savanna and forest soil properties (minipedon analysis)

Soil properties	Crest	Midslople	Valley bottom
ECEC	−47	−22	39
Exchangeable Ca	−38	−2	65
Exchangeable Mg	−35	−40	−46
Exchangeable K	−39	−30	−25
TEB	−37	−10	−59
Total carbon	−15	−58	−22
Total nitrogen	−10	−50	−25
QHg (0−5 cm)	−16	−56	−23
QHg (0−23 cm)	−14	−51	−24

ECEC = Effective Cation Exchange Capacity; TEB = Total Selected Exchangeable Basis

Table 7: Coefficients between soil chemical properties and Hg ($p = 0.05$; $n = 30$) (Pedon values)

Soil properties	R^1	R^2	$1-R^2$
Carbon vs Hg	0.989	0.999	0.021
Total nitrogen vs Hg	0.885	0.782	0.218
ECEC vs Hg	0.822	0.677	0.323
pH vs Hg	0.935	0.874	0.125

ECEC = Effective Cation Exchange Capacity

Conversion of tropical rainforest to grassland provokes a net surface loss of exchangeable basic cations and organic fractions and this is promoted by high rainfall amount, intensity and duration of the tropical study site. With shortened fallow length and increased slash and burn practice, runoff and leaching are encouraged. Similar findings were made by Williams *et al*. (1997) that nutrient leaching contributes to the impoverishment of Amazonian soils.

Differential vegetation seems to affect surface soil Hg distribution as much as it does to fertility factors. Net decreases in total carbon and total nitrogen resulted in net loss of Hg, suggesting that the heavy metal migrates with organic matter fractions. This condition may be driven by burning and volatilization (Roulet *et al*., 1999) or a combination of soil erosion, leaching and increased surface temperature (Fostier *et al*., 2000). Higher values of Hg downs lope is an indication of the prominence of soil erosion closely associated with more exposed grassland soils and consequent deposition of sediments. The role of vegetation and organic fractions is more surficial than sub-surficial as leaching rate may be more prominent in the vertical distribution of Hg in pedons. Leaching effect was more pronounced in savanna soils. Higher Hg levels in savanna soil could be attributed to the use of the site for waste disposal as well as the annual flooding of the Otamiri River which transports wastes across Owerri Municipality and other peri-urban centers. The activities of this river also affect the pedogenesis of studied soils. But the Hg values were above critical level of 0.1 mg kg^{-1} recommended by FEPA (1988), suggesting high possibility of bioavailability and biotoxicity of Hg in studied soils.

Higher Hg burdens in the subsurface horizons irrespective of physiographic position and land use could be due to the release of Hg following exposure of mineral horizons. In both the crest and midslope absolute amounts of surface soil Hg burden were higher in forested landscape having 2.6 and 2.1 mg m^{-2} (forest) and 1.9 and 1.0 mg m^{-2} (savanna), respectively, possibly due to high adsorption of Hg by the organic fractions in the forest soils.

Soil mercury had high correlation values ($R = 0.989$) and ($R = 0.935$) with total carbon and soil pH, respectively (Table 7). With minimal coefficients of alienation ($1-R^2$) of 0.021 and 0.125, both parameters can be used for Hg-predictions in similar landscapes. Significant relationship ($R = 0.885$) was also established between total nitrogen and Hg, implying that Hg migrates with nitrogen out of the pedosphere either through erosion and subsequent leaching and volatilization. However, more intensive soil sampling may be needed for increased reliability on these predictors. But significant correlation coefficients ($p = 0.05$) established when Hg was related with total nitrogen ($R = -0.885$) and ECEC ($R = -0.822$), suggests that both are good predictors of Hg abundance implying that both combined with total carbon and pH could be used in a multiple regression analysis to establish pedotransfer function (models of prediction). This becomes an imperative in precision agriculture and environmental quality. As Hg in the study site is concentrated in deeper layers, it portends danger and vulnerability to groundwater pollution while it becomes less bioavailable to shallow-rooted arable crops in the area.

CONCLUSIONS

The study reveals that disruption of vegetal nature in the rainforest belt of Southeastern Nigeria result in deleterious changes in soil properties. Such changes include losses in soil fertility parameters and exposure to Hg toxicity. Soil Hg toxicity becomes more worrisome in sloping landscapes proximal to aquatic ecosystems since its provoked liberation towards such habitats will lead to the contamination of biologically diverse life in water. It follows that the use of Hg as soil perturbation index can serve to preserve the health of riparian communities in the biosphere.

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