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Reduction in organic matter fractions and structural stability following cultivation of tropical forests in Ethiopia and Nigeria

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A b s t r a c t. The objectives of this study were: to assess changes in the organic matter (OM) fractions of the surface layer (0-20 cm) of the forested Ethiopian and Nigerian soils following their conversion to arable lands, to determine possible changes in the structural stability of these forested soils as they were converted to arable farmland and to evaluate which OM fractions influenced structural stability of these soils most. There were progressive reductions in all OM pools and aggregate stability as the forested soils were cultivated (which were reflected in the soil structure degradation following deforestation); however, the magnitude of reduction was site-specific. The surface soils at Sirinka (Ethiopia) and Umudike (Nigeria) had the highest cultivation-induced reductions in OM (71.7-76.2%), total carbohydrates (R-CHO) (65-76.4%) and humic acids (83.4-95.5%). The humic acids (HA), fulvic acids (FA) and humin (HM) showed a fairly high correlation with MWD of the cultivated soils but the least with forested soils. With microaggregation indices, higher and more significant correlations were obtained. In the forested soils the WSA < 0.25 mm correlated negatively with HA ($r = -0.886$***), FA ($r = -0.607$*), HM ($r = -0.772$**), and with R-CHO ($r = -0.687$*). Also the CDR correlated negatively with HA ($r = -0.828$***), FA ($r = -0.640$*), HM ($r = -0.716$**) and with R-CHO ($r = -0.626$*) in the forested soils. Correlation of these OM fractions with these two micro-structural stability indices were slightly higher in the cultivated than forested soils and substantiate earlier results from the temperate regions in which these OM fractions were more effective in the enhancing of aggregate stability at the micro- than macro-aggregation levels.

K e y w o r d s: organic matter, aggregate stability, tropical soils

INTRODUCTION

Studies on the role of organic matter (OM) in aggregate stability have produced conflicting results. Hamblin and Greenland (1977) found a significant and positive correlation between total organic carbon (OC) and aggregate stability whereas Chaney and Swift (1986) showed that humic substances as components of OM explained aggregate stability better than the total OC concentration. Piccolo and Mbagwu (1990) also observed that humic acid fractions related more positively with aggregate stability than fulvic acid fractions. In the tropical sandy soils of West Africa, Dutarte *et al*. (1993) associated high stability with the humin fraction of OM. In Canada, Angers and Mehuys (1989) showed that the carbohydrates were responsible for the improving of aggregate stability.

These studies were restricted to small sample sizes within generally uniform ecosystems. As the need to obtain more data on OM dynamics in the tropical soils becomes more impelling, studies relating OM to aggregate stability should be carried out with different soils from the contrasting ecosystems. The objectives of our study were i) to assess changes in the OM fractions associated with conversion of tropical forests in Ethiopia and Nigeria to arable cropping; ii) to determine possible changes in structural stability of these forested soils following their conversion to arable lands; and iii) to evaluate which fractions of OM influence structural stability most.

MATERIALS AND METHODS

The present study was carried out on three replicated soil samples from each of the forested and cultivated sites in Ethiopia and southern Nigeria. From September to November 1995, bulk topsoil (0-20 cm) samples, collected from these locations were air-dried, sieved through 4.75 mm

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mesh and shipped to Italy for the determination of aggregate stability by three methods. The first method was the meanweight diameter of water-stable aggregates technique by Kemper and Rosenau (1986) which is a macroaggregation index. The second was a microaggregation index, per cent water-stable aggregates (WSA) < 0.25 mm index. The third was another micro aggregation index, the clay dispersion ratio (CRD) index, calculated as (clay in H_2O/clay in calgon) x 100. The < 2.00 mm fractions were used to measure particle size distributions (after complete dispersion in sodium hexametaphosphate, calgon) by the method of Bouyoucos (1951). The pH level was measured in 1:2.5 soil/water ratio, OC determined by the dichromate, wet oxidation technique and converted to OM by multiplying by 1.724 and CEC by the methods outlined in Anderson and Ingram (1993). Site characteristics are given in Table 1 and the chosen soil properties are shown in Table 2.

Determination of total carbohydrates

Total carbohydrate content was measured on the fine earth fraction by first hydrolyzing 1 g of soil with 10 ml of a 0.25 M H_2SO_4 solution for 16 h in a rotary shaker. Interfering ions in the hydrolisate were reduced by the elusion through anion and cation exchange resins (Martens and Frankenberger, 1993). The monosaccharide content in the hydrolisates was measured colorimetrically as glucose equivalents using the phenol-sulphuric acid method (Piccolo *et al*., 1996).

Determination of humic substances and humin

Dried and sieved soil samples were extracted with 0.1 M $NaOH/NaH_2PO_4$ (1:1, v/v) under N_2, centrifuged and filtered on glass wool. Humic acids were flocculated by acidification of the alkaline extract to pH 2.0 with 6 M HCl and dialyzed against deionized water until chloride-free. They were then freeze-dried and weighed. Fulvic acid was separated from the acid solution on Amberlite XAD – 8 column, re-dissolved in 0.10 M NaOH, dialyzed against deionized water, freeze-dried and weighed. The residue from the above, which contains humin, was treated with 0.10 M $Na_2P_2O_7$, stirred, kept at 85°C for 30 min and centrifuged. The residue left was treated with 0.10 M NH_2OH-HCl at pH 2, stirred for 30 min and then centrifuged. First 10%, then 30% H_2O_2 was added to the residue; it was then digested and 1 M CH_3COONH_4 was added to it, stirred for 1 h and centrifuged for 20 min. The solution with humin was dialyzed against deionized water to wash out salts, freeze-dried and weighed (Stevenson, 1994).

To make the comparison of the effects of land use on the measured properties across all locations easy, we standardized changes in these properties between forested and cultivated sites using the following relationship:

$$\text{Normalized value} = \{1 - (\text{cultivated/forested}) \times 100\}.$$

This made the comparison of changes across all locations valid (Mbagwu *et al*., 1991).

T a b l e 1. Some features of the experimental sites in Ethiopia and Nigeria

Location	Clay mineralogy[1]	Classification soil taxonomy	Region/elevation	Vegetation
Ethiopia				
Awassa	Mi^{+++}; Sm^{++}; K^{+}	Andisol	Central Ethiopian Rift Valley in the south west; 1700 m a.s.l.	Highland savannah
Ghinchi	Sm^{+++}; Mi^{++}; K^{+}	Vertisol	Central highlands; 2400 masl	Savannah
Holeta	Mi^{+++}; K^{++}; Hy^{++}; Sm^{++}	Vertisol	Central highlands; 2400 m a.s.l.	Savannah
Jimma	Mi^{+++}; K^{++}; Hy^{++};	Alfisol	Western region; 1800 masl	Rainforest
Sirinka	Sm^{+++}; Mi^{++}; K^{+}	Vertisol	Tigra region; northern Ethiopia; 1900 m a.s.l.	Advanced soil degradation; little or no vegetation
Nigeria				
Abakiliki	Mi^{+++}; K^{++}; Sm^{+}	Inceptisol	Southeast Nigeria; 430 m a.s.l.	Derived savannah
Nsukka	K^{+++}	Ultisol	Southeast Nigeria; 400 m a.s.l.	Derived savannah
Umudike	K^{+++}	Ultisol	Southeast Nigeria; 80 m a.s.l.	Rain forest

[1]Mi – mica, Sm – smectite, Hy – haloysite, K – kaolonite.

Table 2. Some properties of the surface (0-20 cm) soil samples from Ethiopia and Nigeria

Location/land use	Sand ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	pH (1:2.5 H_2O)	CEC (Cmol(+) kg^{-1})	Na/CEC (%)
Ethiopia						
Awassa						
Forested	425	300	275	6.28	30.4	0.19
Cultivated	425	300	275	6.45	22.6	0.17
Ghinchi						
Forested	25	263	712	5.74	54.4	0.17
Cultivated	25	262	713	5.98	50.0	0.22
Holeta						
Forested	57	238	705	5.58	31.8	0.12
Cultivated	56	240	704	4.88	29.6	0.11
Jimma						
Forested	100	250	650	6.15	30.2	0.14
Cultivated	120	240	640	4.94	26.4	0.11
Sirinka						
Forested	125	350	525	6.02	56.0	0.13
Cultivated	120	335	545	6.75	60.0	0.15
Nigeria						
Abakiliki						
Forested	540	200	260	5.59	34.5	0.33
Cultivated	580	180	240	5.54	23.0	0.37
Nsukka						
Forested	740	40	220	3.53	15.0	0.26
Cultivated	720	40	240	3.87	14.5	0.26
Umudike						
Forested	660	60	280	4.21	24.0	0.33
Cultivated	680	50	270	4.53	11.0	0.22

RESULTS AND DISCUSSION

As shown in Table 1, all Ethiopian soils and Abakiliki soil in Nigeria are dominated by mica and smectite. The rest of the soils in Nigeria are dominated by kaolinite. Three of the Ethiopian soils are Vertisols, one is an Alfisol and another an Andisol. One of the Nigerian soils is a Inceptisol and two are Ultisols. The Ethiopian soils are located at higher elevations (1700-2400 m a.s.l.) than the Nigerian soils (80-430 m a.s.l.).

It is evident that cultivation had no significant effect on the particle size fractions and pH of the Ethiopian and Nigerian soils except in Sirinka and Nsukka (Table 2). Mean weight diameter of water-stable aggregates (MWD) showed consistently higher values in the forested than cultivated soils. Percentage of water-stable aggregates less than 0.25 (WSA < 0.25 mm) and clay dispersion ratio (CDR) had lower values in the forested than cultivated soils. The higher the values of these two indices showed the lower structural stability of the soils (Table 3). Average reductions in MWD in Ethiopia were 37% on Awassa (Andisol), 73% on Ghinchi (Vertisol), 80% on Holeta (Vertisol), 63% on Jimma (Alfisol) and 60% on Sirinka (Entisol). Percentage reductions in MWD of the cultivated sites were lower on the sandier Nigerian than Ethiopian soils and ranged from 7 to 22%. Increases in the values of WSA < 0.25 mm and CDR indices in the cultivated relative to the forested soils imply reductions in the structural stability due to cultivation. A magnitude of such increases is a reflection of the reduction extent in the stability of the soils and for WSA < 0.25 mm, this varied from 1.6% (Ghinchi) to 116.2% (Awassa) in Ethiopia and from 21.7% (Nsukka) to 93.5% (Umudike) in Nigeria. Also for CDR, it varied from 0.7% (Holeta) to 55.2% (Awassa) in Ethiopia and from 13.5% (Nsukka) to 87.9% (Umudike) in Nigeria.

Effects of cultivation on organic matter, total carbohydrates and humic substances

OM levels in the cultivated sites are two to four times lower than in forested sites in both Ethiopia and Nigeria (Table 4). Similar results were obtained for total carbohydrates. Also for more humified fractions of OM, i.e.: humic acids, fulvic acids and humin, there were progressive reductions with cultivation at each site (Table 4). Except of cultivated Ghinchi and Abakiliki sites, cultivation also reduced the HA:FA ratio in other sites (Table 4). A humification index, which is a percentage ratio of HA + FA + HM to OM,

T a b l e 3. Aggregate stability of the surface (0-20 cm) samples from forested and cultivated soils in Ethiopia and Nigeria

Location/land use	MWD (mm)	WSA < 0.25 mm (%)	CDR (%)
Ethiopia			
Awassa			
Forested	0.929	23.5	36.2
Cultivated	0.582	50.8	56.2
LSD (0.05)	0.105	10.1	13.6
Ghinchi			
Forested	1.324	50.8	60.4
Cultivated	0.267	51.6	67.9
LSD (0.05)	0.224	NS	3.4
Holeta			
Forested	1.342	58.9	71.8
Cultivated	0.267	62.4	72.3
LSD (0.05)	0.112	NS	NS
Jimma			
Forested	1.491	50.1	68.2
Cultivated	0.545	61.8	72.1
LSD (0.05)	0.234	6.3	NS
Sirinka			
Forested	1.443	54.5	70.6
Cultivated	0.582	70.3	82.8
LSD (0.05)	0.199	11.9	4.6
Nigeria			
Abakiliki			
Forested	1.878	40.2	48.1
Cultivated	1.741	49.6	58.3
LSD (0.05)	NS	5.8	6.0
Nsukka			
Forested	0.621	56.3	71.0
Cultivated	0.527	68.5	80.6
LSD (0.05)	0.065	4.8	4.9
Umudike			
Forested	0.826	32.1	40.6
Cultivated	0.648	62.1	76.3
LSD (0.05)	0.105	16.0	16.7

NS – not significant.

was significantly higher in the cultivated than forested Awassa, Ghinchi and Abakiliki sites, equal in Holeta and Umudike site but lower in other cultivated sites as compared to forested ones (Table 4).

Surface soils at Sirinka and Umudike had the highest reductions with cultivation in OM (71.7-76.3%), total carbohydrates (65-76.4%) and humic acids (83.4-95.9%). The highest reductions in fulvic acids occurred at Jimma site (68%) whereas that of humin was observed at Jimma (67.7%), Umudike (69.5%), Awassa (74.7%) and Holeta (96.1%) (Table 5).

Our efforts here aimed at the elucidating the effects of deforestation and subsequent cultivation on the soil OM composition and aggregate stability. Reductions in OM pools, arising from cultivation was reported by Dutarte *et al*. (1993) for some sandy West African soils. Also higher reductions in aggregate stability arising from reductions in the proportion of the largest aggregate size (4.75-1 mm), obtained in Ethiopia than Nigeria, may be due to a generally higher initial state of aggregation of the Ethiopian compared to Nigerian forested soils as evidenced by the assessment by means of three structural indices used here. Similar observations were made in other agrocological zones (Beare *et al*., 1994; Cambardella and Elliot, 1993; Gupta and Germida, 1988).

A decrease in the soil OM and its pools in forested soils with cultivation is due to the disintegration of larger aggregates and exposition of the physically-protected, organic materials to microbial oxidation as observed by Hu *et al.* (1995), Salinas-Garcia *et al*. (1997), Franzluebbers and Arshad (1997), and Mbagwu and Piccolo (1998).

Table 4. Organic matter fractions1 (g kg^{-1}) of the surface (0-20 cm) soil samples from Ethiopia and Nigeria as affected by land use

Location/ land use	OM	R-CHO	HA	FA	HM	HA:FA	Humification index (%)
Ethiopia							
Awassa							
Forested	69.5	21.01	15.78	6.91	3.18	2.63	35.9
Cultivated	28.6	14.08	11.56	3.86	1.35	1.80	65.5
LSD (0.05)	11.2	3.54	2.02	2.01	1.28	0.61	18.6
Ghinchi							
Forested	56.5	13.40	11.33	4.03	0.83	4.46	25.9
Cultivated	34.5	9.16	9.11	2.54	0.77	8.36	31.3
LSD (0.05)	14.3	2.45	1.76	1.36	0.03	2.33	3.1
Holeta							
Forested	62.2	14.64	7.67	4.01	1.34	1.91	20.8
Cultivated	27.6	9.88	3.30	2.17	0.77	1.52	20.0
LSD (0.05)	17.8	3.68	2.63	1.13	0.26	0.21	NS
Jimma							
Forested	81.5	12.40	12.50	2.84	1.87	1.83	28.9
Cultivated	34.8	9.28	3.07	2.19	1.35	1.40	18.9
LSD (0.05)	20.4	2.06	5.23	0,07	0.29	0.26	3.7
Sirinka							
Forested	46.9	12.44	10.52	1.37	0.77	8.09	25.8
Cultivated	13.3	4.36	0.43	1.30	0.26	0.35	14.4
LSD (0.05)	5.3	5.72	5.23	0.02	0.31	4.86	4.2
Nigeria							
Abakiliki							
Forested	41.4	16.32	14.23	3.63	2.49	8.23	47.2
Cultivated	17.9	12.39	13.19	3.44	2.28	9.63	95.3
LSD (0.05)	12.4	2.87	0.75	NS	0.08	0.18	21.6
Nsukka							
Forested	20.7	6.90	6.09	1.73	0.91	1.68	51.4
Cultivated	11.7	3.27	1.85	1.27	0.25	1.02	37.9
LSD (0.05)	3.6	2.65	1.92	0.22	0.33	0.41	5.8
Umudike							
Forested	40.7	12.81	15.63	2.48	1.57	6.30	49.1
Cultivated	9.6	3.25	2.59	1.63	1.12	1.59	49.9
LSD (0.05)	5.2	5.58	3.33	1.09	0.36	2.28	NS

Table 5. Normalized changes in organic matter fractions and structural stability of Ethiopian and Nigerian soils

Locations	OM	R-CHO	HA	FA	HM	MWD	WSA < 0.25 mm	CDR
Ethiopia								
Awassa	58.8	33.0	26.7	6.8	74.7	37.3	–116.2	–55.2
Ghinchi	39.0	31.2	19.6	57.1	20.8	72.7	–1.6	–12.4
Holeta	55.7	29.8	57.0	45.9	96.1	80.1	–5.9	–0.7
Jimma	57.3	25.2	75.4	68.0	67.7	63.4	–23.4	–5.7
Sirinka	71.7	65.0	95.9	6.2	3.7	59.7	–29.0	–17.3
Nigeria								
Abakiliki	56.7	24.1	7.3	20.8	30.3	7.3	–23.4	–21.2
Nsukka	43.3	52.6	69.6	49.9	15.4	15.1	–21.7	–13.5
Umudike	76.3	76.4	83.4	34.4	69.5	21.5	–93.5	–87.9

T a b l e 6. Correlation between aggregate stability indices and organic matter fractions for forested (f) and cultivated (c) Ethiopian and Nigerian soils

MWD vs OM fractions	
MWD (forested soils) vs	MWD (cultivated soils) vs
HA (f) = 0.168 NS	HA (c) = 0.532*
FA (f) = 0.006 NS	FA (c) =0.420*
HM (f) = 0.132 NS	HM (c) = 0.674*
R-CHO (f) = 0.302 NS	R-CHO (c) = 0.290 NS
OM (f) = 0.359 NS	OM (c) = – 0.336 NS
WSA < 0.25 mm vs OM fractions	
WSA < 0.25 mm (forested soils) vs	WSA < 0.25 mm (cultivated soils) vs
HA (f) = – 0.889***	HA (c) = – 0.961***
FA (f) = – 0.607*	FA (c) = – 0.896***
HM (f) = – 0.772**	HM (c) = – 0.735**
R-CHO (f) = – 0.687*	R-CHO (c) = – 0.819***
OM (f) = – 0.159 NS	OM (c) = – 0.490*
CDR vs OM fractions	
CDR (forested soils) vs	CDR (cultivated soils) vs
HA (f) = – 0.828***	HA (c) = – 0.986***
FA (f) = – 0.640*	FA (c) = – 0.938***
HM (f) = – 0.716**	HM (c) = – 0.812**
R-CHO (f) = – 0.626*	R-CHO (c) = – 0.858***
OM (f) = – 0.095 NS	OM (c) = – 0.422*

*Significant at p = 0.05, ** significant at p = 0.01, *** significant at p = 0.001, NS – not significant.

Relationship between structural stability indices and organic matter fractions

The relationships shown in Table 6 reveal that in the forested soils OM was not significantly correlated with any of the aggregate stability indices. In the cultivated soil OM negatively and significantly correlated with OM which implies, as expected, that a high OM content in these soils reduced formation of erodible < 0.25 mm aggregates as well as a tendency of the soils to disperse in water. It was also noticed that OM and its fractions could not seriously relate with the MWD index in the forested soils whereas these fractions, except of total carbohydrates (R-CHO), related barely significantly with MWD index in the cultivated soils.

All these OM fractions correlated negatively but significantly with WSA < 0.25 mm and CDR indices of stability (Table 6). These are micro-stability indices and, as expected, these OM fractions operate at this colloidal level of aggregation more than at the macroaggregation level (Piccolo and Mbagwu, 1990; Mbagwu and Piccolo, 1998; Spaccini *et al*., 2001; Spaccini *et al.*, 2002). The magnitude of these correlations between OM fractions and these microaggregation indices of stability was higher in the cultivated than forested soils suggesting that the OM fractions in the cultivate sites are younger than those in the forested sites. In the forested soils HA and HM accounted for most of the variations in these microaggregation indices whereas in the cultivated soils HA and FA were generally more effective than HM and R-CHO in explaining variations in these micro-stability indices.

CONCLUSIONS

1. Organic matter and its fractions in the forested soils of Ethiopia and Nigeria were reduced after cultivation.
2. Structural stability of the soil aggregates which used to be high in the forested soils, was reduced by cultivation.
3. Magnitude of such reductions is site-specific and also related to the initial state of aggregation of these soils.
4. In the forested soil humic acids and humin were responsible for the enhancing of the micro-structural soil stability; whereas in the cultivated soil humic and fulvic acids improved stability indices more than other organic matter fractions.

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