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Carbohydrates in water-stable aggregates and particle size fractions of forested and cultivated soils in two contrasting tropical ecosystems

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Abstract. Information on changes in storage and loss of soil organic carbon (SOC) when tropical forests are converted to cropland is needed for evaluating soil structural degradation and for selecting appropriate sustainable soil management practices. We evaluated changes in SOC storage of organic carbon and acid-hydrolyzable carbohydrates content of aggregated classes and particle size fractions of adjacent forested and cultivated soils in eight agroecosystems from Ethiopian highlands and Nigerian lowlands. In all agroecosystems, SOC content was two to four times higher in the forested than the cultivated soils. Higher SOC content was found in Ethiopian (20.2–47.3 g.kg^{-1}) than Nigerian (12.0–24.0 g.kg^{-1}) forested soils. The magnitude of reduction in SOC and total carbohydrates with cultivation was soil-specific, being generally higher in the sandy than the clayey soils. The smaller aggregate classes (< 1.00 mm) and the sand-sized particles (2000–63 μm) of the forested soils were preferentially enriched in carbohydrates relative to larger aggregates (4.75–1.00 mm). Carbohydrates were more concentrated in the clay-size fraction of the forested than in that of the cultivated soils. Cultivation reduced aggregate stability, increased the proportions of the smaller size aggregates and their associated carbohydrates relative to the forested soils. The susceptibility of the cultivated soils to loss in structural stability reflected this initial aggregation which was greater in the more stable clayey than the fragile sandy soils. The aggregate stability of either the forested or the cultivated soil could not be accounted for by the levels of OC or total carbohydrates in the soil.

Introduction

Conversion of forests to arable lands is usually accompanied by a decline in soil organic carbon (SOC) content. The rate of such decline is influenced by intensity of cultivation, type of soil, texture and dominant mineralogy

(Mbagwu & Piccolo 1998) as well as by the ambient climate which is generally lower in cool temperate than in hot tropical environments (Arrouays & Pelissier 1994). Identification of the magnitude of such management-induced SOC losses and of the most sensitive soil organic matter (SOM) pools affected is needed to select mitigating soil management practices (Adamu et al. 1997). Such identification is important for tropical regions where rates of deforestation are alarming (Lal 1986).

Soil carbohydrates which constitute from 5 to 25% of SOM (Stevenson 1994) are the main component of the labile pool of organic matter (OM) most affected by land use (Cambardella & Elliot 1992). Even though their long-term role in soil physical improvement is still controversial (Piccolo 1996; Degens & Sparling 1996), they are an important source of energy for soil microbial activity (Insam 1996). Extracellular gums and mucilages produced during microbial oxidation of OM are believed to temporarily stabilize soil aggregates (Tisdall & Oades 1982) and thereby protect them against deformation from heavy raindrop impacts which are common at the beginning of rains, especially in the tropics. Because of their labile nature, the effect of soil management practices on the concentrations of carbohydrates are greater than those on the more stable, recalcitrant humified fractions (Piccolo 1996).

Several studies have produced inconsistent results on the effects of land use on both total SOC and concentrations of carbohydrate fractions (Roberson et al. 1991; Dalal & Henry 1988; Arshad et al. 1990; Benzing-Purdie 1980). For example, Roberson et al. (1991) observed that after 2 years of conventional tillage in an orchard in California, soil carbohydrates were of the same level as those in the untilled plots. Arshad et al. (1990) and Hu et al. (1995) reported however, that long-term tillage reduced soil carbohydrates. Such differences in results may be related to texture, soil type, original soil carbon level and quality, and the distribution of natural aggregates in soils (Mbagwu & Piccolo 1998). In hot, humid southern Nigeria, Mbagwu and Piccolo (1998) observed that carbohydrates and SOC decreased with decreasing wet-aggregate diameter, whereas in the cool plateau region of central Nigeria, Adamu et al. (1997) using the same types of soils, reported that smaller dry aggregates were preferentially enriched in OC relative to the macroaggregates. This indicates possible confounding influences of environment and the type of aggregates studied (i.e., whether wet- or dry-sieved). In Canada, Smith et al. (1997) computed a total loss of 1.93 $t.ha^{-1}$ of SOC (equivalent to 7.08 t of CO_2) from agricultural lands, with higher rates in coarse- than fine-textured soils. Chesire et al. (1990), in a long-term incubation study with ^{14}C-labelled barley, found that carbohydrate contents in size fractions were in the order: sand > silt > clay, which is similar to the results obtained by Angers and Mehuys (1990).

With few exceptions (Beare et al. 1994; Elliot 1986), most of these studies have concentrated on whole soil fractions (< 2.0 mm) and have focused on few soils within similar ecosystems. While this approach gives a generalized overview of the total carbohydrate content in soils, a proper understanding and modeling of SOM dynamics requires an evaluation of the locations of these labile OM pools within aggregates and particle size fractions. Their precise location gives an indication of their potential accessibility for microbial degradation (Cheshire & Mundie 1981; Angers & N'Dayegamiye 1991). To obtain more general results and to facilitate extrapolation of results, more extensive regional data are needed on the effects of land use, texture, elevation, climate and soil types on storage and loss of OC when forests are converted to permanent arable farming (Davidson & Ackerman 1993; Arrouays & Pelissier 1994).

This paper presents the results of our study on the distribution of acid-hydrolyzable carbohydrates in whole soils (< 2.0 mm diameter), water-stable aggregates and particle size fractions of forested and cultivated soils in different agroecosystems in sub-saharan Africa. The objectives were (1) to evaluate changes in carbohydrate concentrations in whole soils, aggregates and particle size fractions of soils before and after deforestation and subsequent arable farming and (2) to relate such changes to aggregate stability of the soils.

Materials and methods

Description of sites, experimental design and soil sampling

This study was conducted with soils from low-input agricultural systems in Ethiopia and southern Nigeria. This low-input agricultural system is such that forested sites are cleared for arable cropping without further inputs of organic or inorganic fertilizers. Also cultivation consists essentially of hand hoeing and planting without mechanical tillage in all sites but Holeta, Jimma and Umudike where mechanical cultivation (disking, ploughing and harrowing) was used. Relevant information on the sites is given in Table 1.

In each location the experimental set up was a Randomized Complete Block Design with each treatment replicated three times. The treatments were forested and cultivated sites. In Ethiopia, each plot size measured 6 m $\times$ 4 m, whereas in Nigeria each plot size was 6 m $\times$ 5 m. From September to November 1995, three bulked topsoil (0–20 cm) samples, collected from each replicate of the forested and cultivated sites in these locations, were air-dried, sieved through 4.75 mm mesh and shipped to Italy for determination of water-stable aggregates and carbohydrates. The < 2.00 mm (fine earth)

Table 1. Locations soils and land use histories of the sites studied.

Locations	Land use histories
	ETHIOPIA
Awassa: 06° 58′N, 38° 25′E; Alt. 1700 m.a.s.l. Soil: Andisol; Annual rainfall: 1100 mm. Drainage class: Rapid. Parent Material: Volcanic Ash. Vegetation: Highland Savannah	Located at the centre of the Rift Valley in the southwest part of Ethiopia; climax vegetation which represents the forested soil is highland savannah whereas the cultivated soil has been cropped for 4 years (1992–1995) and grown annually to maize.
Ginchi: 09° 01′N, 38°20′E; Alt. 2300 m.a.s.l. Soil: Vertisol; Annual rainfall: 900 mm. Drainage class: Moderate Parent Material: Weathered Basalt Vegetation: Secondary Forest	Located at the central highlands; forest site is a secondary forest not cultivated for < 35 years and the cultivated soil has been planted to wheat and barley for 4 years (1992–1995)
Holeta: 09° 03′N, 38°30′E; Alt. 2400 m.a.s.l. Soil: Vertisol; Annual rainfall: 1054 mm Drainage class: Rapid Parent Material: Olivine Basalt Vegetation: Secondary Forest	Also located in the central highlands with vegetation similar to Ghinchi. Forested soil is a secondary regrowth not cultivated for about 20 years; cultivated soil has been grown to wheat and barley for 4 years (1992–1995).
Jimma: 07° 41′N, 36° 50′E; Alt. 1800 m.a.s.l. Soil: Alfisol; Annual rainfall: 1400 mm Drainage class: Rapid Parent Material: Basalt Vegetation: Rainforest	Located in the western part with rainforest vegetation as the climax vegetation. The cultivated soil has been cropped to maize for 5 years (1988–1992) without returning maize residues to the soil.
Sirinka: 11° 62′N, 39° 70′E; Alt. 1900 m.a.s.l. Soil: Entisol; Annual rainfall: 700 mm Drainage class: Moderate Parent Material: Alluvial Deposits Vegetation: Bush regrowths	Located in the highly degraded Tigrai region of northern Ethiopia where the climax vegetation is bush regrowths no cultivated for about 15 years. The cultivated soil has been cropped continuously to sorghum for 5 years (1988–1998)

Table 1. Continued.

Locations	Land use histories
	NIGERIA
Abakiliki:	
06° 30′N, 08° 15′E, Alt. 200 m.a.s.l. Soil: Gravelly Inceptisol; Annual rainfall: 1560 mm Drainage class: Slow Parent Material: Shale Deposits Vegetation: Derived Savannah	Forested soil is revegetated with Gmelina trees (established in 1960). Cultivated soil site is continuously cultivated for 5 years (1991–1995) with maize-vegetables-upland rice/soybean-maize/cowpea rotation.
Nsukka:	
06° 51′N, 07° 24′E, Alt. 400 m.a.s.l. Soil: Ultisol; Annual rainfall: 1600 mm Drainage class: Very rapid Parent Material: False-bedded Sandstones Vegetation: Derived Savannah	Forested soil represents the climax vegetation not affected by annual bush burning. Cultivated soil has been cultivated annually to cassava for 5 years (1991–1995).
Umudike:	
05° 29′N, 07° 33′E, Alt. 120 m.a.s.l. Soil: Ultisol, Annual rainfall: 2100 mm Drainage class: Very rapid Parent Material: Sedimentary Rocks Vegetation: Humid Rainforest	Forested soil is climax vegetation (> 100 years old) and the cultivated soil has been continuously cropped to cassava for 15 years.

fractions were used to measure particle size distributions (after complete dispersion with sodium hexametaphosphate) by the pipette method of Gee and Bauder (1986). pH was measured in 1:2.5 soil-water ratio, OC by the wet oxidation procedure of Nelson and Sommers (1982), and NH_4-acetate exchangeable bases and CEC following procedures outlined in Anderson and Ingram (1993). Total carbohydrate content was measured in this whole soil fraction by the phenol-sulphuric acid method described below (Piccolo et al. 1996). All determinations were made on each of the replicated samples. The pertinent soil properties shown in Table 2 indicate significant redistribution between silt and clay for Holeta, Jimma, and Umudike due apparently to the use of mechanical cultivation (which involves soil inversion) in the cultivated sites and wind erosion effects.

Table 2. Some properties of the 0–20 cm of the forested (F) and cultivated (C) soils.

Location/ land use	Sand (g/kg)	Slit (g/kg)	Clay (g/kg)	pH (H_2O)	TEB[1] (Cmol/kg)	CEC[2] (Cmol/kg)
ETHIOPIAN SOILS						
Awassa						
F	425	300	275	5.28	16.29	30.4
C	425	300	275	5.45	11.36	22.6
Ginchi						
F	25	263	712	5.74	29.41	54.4
C	25	263	712	5.98	29.11	54.0
Holeta						
F	57	238	705	5.58	10.55	31.8
C	0	163	837	4.88	4.12	29.6
Jimma						
F	100	250	650	6.15	16.07	30.2
C	25	143	823	4.94	7.74	26.2
Sirinka						
F	225	250	525	6.02	34.61	56.0
C	275	212	513	6.75	25.40	60.0
NIGERIAN SOILS						
Abakiliki						
F	540	200	260	5.59	16.40	34.5
C	580	180	240	5.54	7.23	23.0
Nsukka						
F	740	40	220	3.53	0.99	15.0
C	700	20	280	3.87	4.27	14.5
Umudike						
F	660	60	280	4.21	6.93	24.0
C	820	20	160	4.53	1.84	11.0

[1]TEB is total exchangeable bases.
[2]CEC is Cation exchange Capacity.

Separation of water-stable aggregates and determination of aggregate stability

The method of Kemper and Rosenau (1986) was used to separate water-stable aggregates. Twenty grams of the < 4.75 mm air-dried soil were put in the topmost of a nest of three sieves of 1.00, 0.50, and 0.25 mm mesh size and pre-soaked in distilled water for 30 min. Thereafter the nest of sieves and its contents were oscillated vertically in water 20 times using a 4 cm amplitude at the rate of one oscillation per s. Care was taken to ensure that the soil particles on the topmost sieve were always below the water surface during each oscillation. After wet-sieving, the resistant soil materials on each sieve and the unstable (< 0.25 mm) aggregates were quantitatively transferred into beakers, dried in the oven at 50 °C for 48 h, weighed and stored for analysis of carbohydrates. The percentage ratio of the aggregates in each sieve represents the water-stable aggregates (WSA) of size classes: 4.75–1.00 mm, 1.00–0.50 mm, 0.50–0.25 mm and < 0.25 mm. Due to our interest in also studying the carbohydrate distribution in the particle size fractions we did not correct the WSA for the sand particles that may have co-settled with the aggregates on the sieves. Aggregate stability was measured as the mean-weight diameter (MWD) of water-stable aggregates as by equation 1:

$$\mathrm{MWD} = \sum_{i=1}^{n} X_i W_i \tag{1}$$

where, X_i is the mean diameter of the i^{th} sieve size and W_i is the proportion of the total aggregates in the I^{th} fraction. Higher MWD values indicate higher proportions of macroaggregates in the sample and therefore, higher stability.

Separation of particle size fractions

The coarse sand (2000–200 μm), fine sand (200–63 μm), silt (63–2 μm) and clay (< 2 μm)-sized fractions were separated from the < 2.00 mm particles without prior chemical pretreatment. Low sonication energy was used to disperse the soils so as to simulate natural disruptive forces such as from raindrop impact and avoid organic matter redistribution among the separates. The procedure (carried out in triplicate per sample) is the one described by Stemmer et al. (1997) and consisted of suspending 40 g of the < 2.0 mm, air-dried sample in 100 mL of deionized water in a beaker and dispersing with an ultrasonic probe (Ultrasonic Liquid Processor, XL-Series Sonicator) placed at about 1 cm depth from the soil-water suspension. The suspension was sonicated for 2 min yielding a total energy of 240 J (or 2.40 J mL^{-1}). The dispersed soil was then wet-sieved through a series of sieves to separate the coarse sand and fine sand. The silt fraction was separated through centrifugation at 90 g for 6 min. To maximize the silt yield, centrifugation was repeated two more times on the residue. The clay fraction was separated from the supernatant after centrifugation at 3100 g for 30 min. These fractions were air-dried, weighed and stored for determination of total carbohydrates. In both determinations of WSA and particle size fractions variation within triplicates of reference samples was less than 5%.

Determination of total carbohydrates

For more detailed study of the distribution of carbohydrates within these samples, carbohydrate content was measured in duplicate per sample on the water-stable aggregates and particle-size fractions (separated as described above) by first hydrolyzing 1 g of soil by shaking for 16 h with 10 mL of a 0.25 M H_2SO_4 solution in a rotary shaker. Interfering ions in the hydrolyzate were reduced by elution through anion and cation exchange resins (Martens & Frankenberger 1993). The monosaccharide content in the hydrolyzates was measured colorimetrically as glucose equivalents using the phenol-sulphuric acid method (Piccolo et al. 1996). All measurements were expressed as glucose concentrations in $g.kg^{-1}$ of the water-stable aggregates or the particle-size fractions.

Data analysis

Simple correlations between MWD and SOC or total carbohydrates were used to evaluate their possible contribution to soil structural stability. For each site an analysis of variance (ANOVA) for Randomized Complete Block Design (RCBD) was used to compare the effects of land use on the measured properties. Where the F-values were significant at $P = 0.05$ level, the least significant differences (LSD) were calculated and used to compare the mean values of the forested and cultivated treatments. For ease of comparing the effects of land use on aggregate stability (AS) across all locations, the change in MWD between forest and cultivated sites was normalized as follows:

$$AS_v = \{1 - (MWD_c/MWD_f)\} \times 100 \quad (2)$$

where, AS_v is the normalized MWD and subscripts c and f refer to cultivated and forested sites, respectively. In this way, comparison of the changes in structural stability and in SOC and carbohydrates across all locations becomes valid (Mbagwu et al. 1991).

Results

Effects of cultivation on water-stable aggregates and aggregate stability

Table 3 shows that irrespective of site, the proportion of the largest aggregate class (4.75–1.00 mm) decreased with cultivation. In Ethiopia cultivation reduced the proportion of water-stable aggregates between 51 and 97% relative to the five forested soils. In Nigeria, cultivation reduced the proportion of the water-stable aggregates between 6 and 61% relative to the three forested soils, showing a generally lower impact of cultivation on the sandy than clayey soils. Also with the exception of the gravelly soil from Abakiliki, soils with initial high percent of water-stable macroaggregates tended to be more susceptible to reduction in this aggregate-size range with cultivation.

At each site in Ethiopia, cultivation increased substantially the proportion of < 1.00 mm aggregate class. The average increases ranged from 45% to 70% for the forested sites and from 85% to 96% for the cultivated sites. The Vertisols were the most susceptible to the cultivation-related increase in small (< 1.00 mm) aggregates. In Nigeria the average forested and cultivated values were 67% and 75%, respectively. Hence deforestation and intensive arable farming on these soils reduced water-stable aggregates to smaller diameters. This was also reflected in the aggregate stability index used (MWD) which showed consistently higher values in the forested than in cultivated sites (Table 4). In Ethiopia the average reductions in MWD were 76% on the Vertisols, 63% on the Alfisol, 60% on the Entisol and 37% on the Andisol (Table 5). Reductions in MWD of the cultivated soils were less in sandier Nigerian than Ethiopian soils, and ranged from 7 to 22%.

Effects of cultivation on organic carbon and total carbohydrate contents

In Ethiopian forested soils (Table 4), OC ranged from 27.2 g kg^{-1} (in Sirinka) to 47.3 g kg^{-1} (in Jimma), whereas OC content in Nigerian forested soils varied between 12.0 g kg^{-1} (in Nsukka) and 24.0 g kg^{-1} (in Abakiliki). The OC in cultivated sites was 50 to 75% lower than in forested sites. Similar results were obtained for total carbohydrates. Relative to the forested soils the largest reductions in OC occurred in the cultivated sandy Sirinka (72%) and Umudike (76%) soils (Table 5). The surface soil at these locations also had the largest reductions in carbohydrate content (65% and 75%, respectively).

Table 3. Distribution of water-stable aggregates (WSA, %) in forested (F) and cultivated (C) soils in Ethiopia and Nigeria.

Location/	Size fractions of WSA (mm)			
land use	4.75–1.00	1.00–0.50	0.50–0.25	< 0.25
		ETHIOPIAN SOILS		
Awassa				
F	30.3	19.2	19.8	30.7
C	14.8	29.0	25.0	31.2
LSD (0.05)	5.6	6.1	3.8	NS
Ginchi				
F	47.4	10.7	7.0	34.9
C	7.2	11.6	18.0	63.2
LSD (0.05)	9.8	NS	5.5	11.4
Holeta				
F	47.4	16.4	11.7	24.2
C	1.2	7.0	31.8	60.0
LSD (0.05)	10.3	4.5	8.2	11.1
Jimma				
F	53.1	15.0	11.8	20.1
C	13.0	21.5	29.0	36.5
LSD (0.05)	8.9	3.3	8.8	9.3
Sirinka				
F	55.3	18.2	7.7	18.8
C	11.7	39.4	24.5	24.4
LSD (0.05)	10.9	6.6	8.6	NS
		NIGERIAN SOILS		
Abakiliki				
F	63.0	13.6	7.0	16.4
C	59.2	9.0	6.1	25.7
LSD (0.05)	NS	2.3	NS	4.4
Nsukka				
F	14.7	33.2	26.7	25.4
C	5.8	36.4	37.9	19.9
LSD (0.05)	3.5	NS	9.1	4.9

Table 3. Continued.

Location/ land use	Size fractions of WSA (mm)			
	4.75–1.00	1.00–0.50	0.50–0.25	< 0.25
Umudike				
F	19.8	37.8	19.1	23.3
C	8.8	58.1	15.8	17.3
LSD (0.05)	7.2	11.5	NS	4.8

NS = Not significant.

The regression equations relating aggregate stability (AS) with OC and carbohydrates for all the Ethiopian and Nigerian forested (F) or cultivated (C) soils are:

$$\mathrm{AS}(F) = 0.827 + 0.013(\mathrm{OC}) \quad (\mathrm{R}^2 = 0.13)(\mathrm{N} = 8) \tag{3}$$

$$\mathrm{AS}(C) = 0.958 - 0.023(\mathrm{OC}) \quad (\mathrm{R}^2 = 0.09)(\mathrm{N} = 8) \tag{4}$$

$$\mathrm{AS}(F) = 0.808 + 0.031(\mathrm{Carbohydrates}) \quad (\mathrm{R}^2 = 0.23)(\mathrm{N} = 8) \tag{5}$$

$$\mathrm{AS}(C) = 0.381 + 0.031(\mathrm{Carbohydrates}) \quad (\mathrm{R}^2 = 0.09)(\mathrm{N} = 8) \tag{6}$$

None of the R^2 values in eqs. 3–6 are significant, explaining only 9 to 13% of variation in AS with the level of OC present and between 9% and 23% of variation in AS with the level of carbohydrates in soils. Possible explanations for these low correlations are (i) that other SOC fractions are responsible for stabilizing aggregates in these soils (Monreal et al. 1995; Dinel et al. 1997; Piccolo & Mbagwu 1999), and (ii) that reduction in aggregate stability was due mainly to physical disintegration of the larger aggregates to smaller sizes due to tillage implements.

Distribution of total carbohydrates in water-stable aggregates

In the forested sites, the smaller aggregate classes (< 1.00 mm) were preferentially enriched in total carbohydrates as compared with the large (4.75–1.00 mm) aggregates (Table 6). The carbohydrates stored in the small (< 1.00 mm) aggregates of the forested soils ranged from 7.2 g kg^{-1} (Nsukka) to 16.6 g kg^{-1} in Awassa whereas the concentrations of those stored in the macroaggregate classes (> 1.00 mm) were lower and varied between 2.0 g kg^{-1} (Nsukka) and 5.3 g kg^{-1} (Abakiliki) (Table 6). This indicates that the carbohydrates are better protected in the smaller than in the larger size aggregates of the forested soils. With cultivation the concentration of carbohydrates in these smaller class aggregates was reduced in absolute values but were still

Table 4. Differences in aggregate stability, organic carbon (OC) and total carbohydrates of forested (F) and cultivated (C) soils in Ethiopia and Nigeria.

Location/ land use	Aggregate Stability (MWD, mm)	OC (g/kg)	Total carbohydrates (g/kg)	Proportion of carbohydrates in < 0.25 mm, (%)	Carbohydrates in (< 1.0 mm)/ Carbohydrates in (> 1.0 mm)
ETHIOPIAN SOILS					
Awassa					
F	0.928	40.3	21.0	33.7	3.73
C	0.582	16.6	14.1	22.5	2.39
LSD (0.05)	0.105	6.5	3.54	7.18	0.97
Ginchi					
F	1.324	32.8	13.40	19.8	4.09
C	0.362	20.0	9.16	43.8	2.52
LSD (0.05)	0.244	8.3	2.45	2.20	1.10
Holeta					
F	1.342	36.1	14.64	13.6	3.85
C	0.267	16.0	9.88	23.2	0.90
LSD (0.05)	0.112	10.3	3.68	3.82	2.05
Jimma					
F	1.491	47.3	12.40	19.1	3.16
C	0.545	20.2	9.28	22.6	3.03
LSD (0.05)	0.234	11.9	2.06	2.75	0.15
Sirinka					
F	1.443	27.2	12.44	44.3	3.08
C	0.582	7.7	4.36	47.9	0.33
LSD (0.05)	0.199	3.1	5.72	3.8	2.00
NIGERIAN SOILS					
Abakiliki					
F	1.878	24.0	16.32	50.1	2.09
C	1.741	10.4	12.39	60.1	1.93
LSD (0.05)	NS	7.2	2.87	7.70	0.17
Nsukka					
F	0.621	12.0	6.90	50.4	2.38
C	0.527	6.8	3.27	54.1	0.01
LSD (0.05)	0.065	2.1	2.65	4.6	1.75

Table 4. Continued.

Location/ land use	Aggregate Stability (MWD, mm)	OC (g/kg)	Total carbohydrates (g/kg)	Proportion of carbohydrates in < 0.25 mm, (%)	Carbohydrates in (< 1.0 mm)/ Carbohydrates in (> 1.0 mm)
Umudike					
F	0.826	23.6	12.81	15.7	2.63
C	0.648	5.6	3.25	32.3	3.06
LSD (0.05)	0.105	3.0	6.58	11.38	0.30

Table 5. Normalized changes (%)[1] in soil organic carbon (OC), total carbohydrates and aggregate stability from forested to cultivated soils in Ethiopia and Nigeria.

Locations	OC	Total carbohydrates	Aggregate stability
	ETHIOPIAN SOILS		
Awassa	58.8	33.0	37.3
Ginchi	39.0	31.2	72.7
Holeta	55.7	29.8	80.1
Jimma	57.3	25.2	63.4
Sirinka	71.7	65.0	59.7
	NIGERIAN SOILS		
Abakiliki	56.7	24.1	7.3
Nsukka	43.3	52.6	15.1
Umudike	76.3	74.6	21.5

[1]Normalized value = [1 − (cultivated-value/forested-value)] × 100. All values indicate percentage reduction relative to forests.

better protected in these aggregates than in the larger ones. The ratio of carbohydrates in the < 1.00 mm aggregates to that in the > 1.00 mm aggregates of the forested soils varied between 2.1 to 4.1, thereby indicating a two- to four-fold increase in carbohydrates stabilization.

In all aggregate sizes, cultivation reduced carbohydrate concentrations (Table 6). Hence the ratios of their distribution in the < 1.00 mm to the > 1.00 mm aggregates were generally lower in the cultivated than in the forested soils (Table 4). Also the proportion of carbohydrates in the < 0.25 mm aggregates of the forested soils varied between 13.6% (in Holeta)

Table 6. Concentrations of carbohydrates (g/kg) in water-stable aggregate (WSA) classes of forested (F) and Cultivated (C) soils in Ethiopia and Nigeria.

Location/ land use	Water Stable Aggregate Classes (mm) 4.75–1.00	1.00–0.50	0.50–0.25	< 0.25
	ETHIOPIAN SOILS			
Awassa				
F	4.44	4.58	4.92	7.07
C	4.18	4.40	2.35	3.17
LSD (0.05)	0.27	0.09	1.27	1.59
Ghinchi				
F	2.64	2.29	1.58	2.65
C	2.60	2.81	3.60	4.01
LSD (0.05)	0.07	0.37	1.48	0.96
Holeta				
F	3.02	2.47	2.41	1.99
C	5.20	3.34	3.82	2.29
LSD (0.05)	1.45	0.56	1.00	0.21
Jimma				
F	2.98	4.33	2.72	2.37
C	2.30	2.46	2.43	2.10
LSD (0.05)	0.48	1.32	0.42	0.20
Sirinka				
F	3.05	1.87	1.99	5.51
C	3.27	1.30	1.69	2.09
LSD (0.05)	0.26	0.43	0.22	2.42
	NIGERIAN SOILS			
Abakiliki				
F	5.28	10.00	9.16	8.17
C	4.23	7.30	5.80	7.45
LSD (0.05)	0.47	1.83	2.75	0.91
Nsukka				
F	2.04	1.92	1.77	3.48
C	3.23	2.02	1.75	1.77
LSD (0.05)	0.84	0.17	0.04	1.21

Table 6. Continued.

Location/ land use	Water Stable Aggregate Classes (mm)			
	4.75–1.00	1.00–0.50	0.50–0.25	< 0.25
Umudike				
F	3.53	1.91	1.86	2.01
C	0.84	0.87	0.78	1.05
LSD (0.05)	1.39	0.75	0.76	0.69

and 50.4% (in Abakiliki) whereas in the cultivated soils it ranged from 22.5% (in Awassa) to 60.1% (in Abakiliki). This trend shows, therefore, that as forests are converted to arable lands, there is a preferential accumulation of carbohydrates in small aggregates < 1.00 mm diameter (Table 4).

Distribution of carbohydrates in particle size fractions

Irrespective of land use, the highest carbohydrate concentrations occurred in the total sand-sized fraction (2000–63 μm) (Table 7). Most of the forested, clay-sized fraction accumulated more carbohydrates than the silt-sized fraction whereas in most of the cultivated soils the silt-sized fraction contained more carbohydrates than the clay-sized fraction. This shows that in most sites, carbohydrates are protected more in clay-sized fractions under forest than under cultivation apparently because the clay-sized fractions have large surface areas and can adsorb carbohydrates which may be further protected in strong clay-OM complexes.

In three of the Ethiopian sites (Ginchi, Holeta and Sirinka), cultivation increased the concentrations of carbohydrates in the clay fraction while reducing them in the sand fraction as compared to forested soils (Table 7). No significant change was observed between the carbohydrate concentrations in the clay fractions of forested and cultivated Awassa soils. Cultivation decreased carbohydrate concentrations in all particle size fractions of Jimma soil. In Nigeria, cultivation also decreased carbohydrates in all size fractions at Abakiliki and only in the sand and clay fractions at Umudike (Table 7). At Nsukka, cultivation caused an increase in soil carbohydrate concentrations consistently in all size fractions.

Table 7. Concentrations of carbohydrates (g/kg) in particle size fractions of forested (F) and cultivated (C) soils in Ethiopia and Nigeria.

Location/ land use	Coarse sand (2000–200 μm)	Fine sand (200–63 μm)	Total sand (2000–63 μm)	Silt (63–2 μm)	Clay (< 2 μm)
			ETHIOPIAN SOILS		
Awassa					
F	3.54	3.92	7.46	5.12	2.19
C	2.25	2.37	4.62	1.97	2.01
LSD (0.05)	0.81	0.85	1.48	1.56	NS
Ghinchi					
F	2.00	2.04	4.04	0.35	0.95
C	0.75	3.00	3.75	1.57	1.36
LSD (0.05)	0.63	0.71	NS	0.83	0.22
Holeta					
F	2.99	2.90	5.89	2.50	1.01
C	1.69	2.93	4.62	3.14	1.89
LDS (0.05)	0.42	NS	0.74	0.32	0.51
Jimma					
F	5.47	4.23	9.70	4.96	5.33
C	4.81	3.19	8.00	3.91	3.03
LSD (0.05)	0.54	0.62	1.32	0.85	1.09
Sirinka					
F	3.27	4.53	7.80	4.26	4.45
C	5.70	7.30	13.00	6.92	4.93
LSD (0.05)	1.30	1.56	3.46	1.77	NS
			NIGERIAN SOILS		
Abakiliki					
F	3.56	4.46	8.02	3.42	4.00
C	3.74	2.94	6.68	1.59	3.13
LSD (0.05)	NS	0.65	1.16	0.92	0.60
Nsukka					
F	0.87	1.64	2.51	2.24	0.96
C	1.08	1.74	2.80	2.50	1.40
LSD (0.05)	0.08	NS	0.26	0.20	0.28

Table 7. Continued.

Location/ land use	Coarse sand (2000–200 μm)	Fine sand (200–63 μm)	Total sand (2000–63 μm)	Silt (63–2 μm)	Clay (< 2 μm)
Umudike					
F	1.26	1.37	2.63	1.39	2.23
C	0.62	1.64	2.26	1.61	2.14
LSD (0.05)	0.39	0.21	0.29	0.18	NS

NS = Not significant.

Discussion

We concentrated on effects of deforestation and subsequent cultivation on soil organic matter storage, quality, and aggregate stability. In Africa, this low-input system represents an extensive worst-case scenario for studying SOM and aggregate degradation processes arising from long-term continuous cultivation. Our observation of reductions in the proportion of macroaggregates (> 0.25 mm) following cultivation was also reported in other ecosystems. For example, on a sandy clay loam from Georgia, USA, Beare et al. (1994) obtained higher proportion of macroaggregates under zero than conventional-tillage practices. Cambardella and Elliot (1993) and Gupta and Germida (1988) reported higher proportions of microaggregates (< 0.25 mm) when native grasslands were cultivated. The greater reduction in proportion of the largest aggregate size (4.75–1.00 mm) obtained in Ethiopia than Nigeria may be due to the generally higher initial aggregation of Ethiopia compared to Nigeria forested soils. In Ethiopia, the average proportion of < 1.00 mm aggregates in the cultivated soils varied in the order: Holeta (99%) > Ginchi (93%) > Sirinka (88%) > Jimma (87%) > Awassa (85%) and in Nigeria, Nsukka (94%) > Umudike (91%) > Abakiliki (41%). The latter shows that the Ethiopian Vertisols and the Nigerian Ultisols are more susceptible to reduction in the proportion of larger aggregates following cultivation than in other soils.

The decrease in total SOC and carbohydrates in forested soils with cultivation is attributed to disintegration of the larger aggregates and consequent exposure to microbial oxidation of the partially decomposed organic materials previously protected in the disintegrated aggregates (Dalal & Henry 1988; Cambardella & Elliot 1993). Roberson et al. (1991) reported earlier that tillage had no significant effect on the OC content of a loamy soil from California (USA) which is the reverse of our observation. A number of papers (Hu et al. 1995, and Salinas-Garcia 1997 in USA; Chan 1997 in Australia; Arshad et al. 1990; Baldock et al. 1987; Angers & Mehuys 1989, and Franzluebbers & Arshad 1997 in Canada and Mbagwu & Piccolo, 1998 in Nigeria) reported results similar to those of our study. Recently Parfitt et al. (1997) related the stability and turnover time of OC with mineralogy of Al and Fe oxides by suggesting that SOC was stabilized more in soils with higher amount of allophane and ferrihydrite (eg. Andisols) than in other soils. Monreal et al. (1997) and Monreal and Kodama (1997) while agreeing with the findings of Parfitt et al. (1997) for OC, noted that the carbohydrate fraction was not affected by such abiotic stabilization reactions with the oxides of Fe and Al. In our study the percentage loss of OC in the Andisol (Awassa) was the second highest in Ethiopia, which indicates no such preferential stabilization of OC in this Andisol.

The general trend of the smaller forest aggregates to be preferentially enriched in total carbohydrates was also reported by Webber (1965). A possible explanation could be that carbohydrates in smaller aggregates are more strongly adsorbed as polymers of various forms and dimensions to either clay or humic fractions which abound in the microaggregates (Stevenson 1994; Piccolo & Mbagwu 1990). In this way the carbohydrates are better protected from microbial degradation than those in the larger aggregates, hence their higher concentrations in the smaller aggregate fractions. The cultivation-induced reduction of carbohydrates in aggregates > 1.00 mm and their corresponding increase in aggregates < 1.00 mm of most of these soils supports the findings of Cambardella and Elliot (1993). Likewise, Dalal and Henry (1988) proposed that destruction of macroaggregates by cultivation exposes physically protected organic materials to rapid oxidation and loss. This hypothesis was later confirmed by Monreal et al. (1997) who showed that SOC in macroaggregates $> 250\ \mu$m was young and turned over in 14 years.

Irrespective of site and cultivation history, the total sand fraction had the highest concentration of carbohydrates. Loss of carbohydrates from sands following cultivation varied from 7% in clayey Ginchi to 38% in sandy Awassa. During an initial period of cultivation, Dalal and Mayer (1986) also reported rapid loss of sand-sized OM (which was equivalent to their particulate OM fraction).

The lack of a strong relationship between aggregate stability and OC or carbohydrates in this study suggests that other binding agents may be involved in stabilizing the aggregates in these soils. Carbohydrates have been previously associated with improvements in soil aggregate stability (Angers & Mehuys 1989; Haynes & Swift 1990; Angers et al. 1993; Haynes & Francis 1993). However, according to Insam (1996), since carbohydrates are easily degraded by microorganisms, they cannot participate in long-term stabilization of soil aggregates. The short term effect of a polysaccharide on soil aggregate stability was recently confirmed by Piccolo and Mbagwu (1999). Dutarte et al. (1993) associated aggregate stability on intensively cultivated sandy soils from West Africa with the humified fractions of organic matter, notably humin and humic acids. Earlier studies (Piccolo & Mbagwu 1990; Mbagwu & Piccolo 1998) also reported a significantly higher positive correlation between microaggregate stability and humic acid content than either total OC or the carbohydrate contents. Carbohydrates have been shown to participate in the process of aggregate stabilization when acting in conjunction with the more humified soil organic matter pools (Angers & Mehuys 1989; Caron et al. 1992; Piccolo & Mbagwu 1999). Hence isolating carbohydrates alone and testing statistically their effect on aggregate stability indicates weak relationships as observed in this study.

In conclusion, these results show that continuous cultivation following deforestation reduced the proportion of the largest aggregate class (4.75–1.00 mm) and the content of carbohydrates and OC in these aggregates. The OC and carbohydrates contents of these soils did not account, however, for the variation in aggregate stability of these soils.

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