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Riccardo Spaccini
University of Naples Federico II

Charles Igwe
University of Nigeria

Pellegrino Conte
Università degli Studi di Palermo

Alessandro Piccolo
University of Naples Federico II

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Carbohydrates and aggregation in lowland soils of Nigeria as influenced by organic inputs

R. Spaccini [a], J.S.C. Mbagwu [b], C.A. Igwe [b], P. Conte [a], A. Piccolo [a,*]

[a] *Dipartimento di Scienze del Suolo, della Pianta e dell'Ambiente, Università di Napoli Federico II, Via Università 100, 80055 Portici, Italy*
[b] *Department of Soil Science, University of Nigeria, Nsukka, Nigeria*

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Abstract

We evaluated the influence of several organic matter management practices on the characteristics of carbohydrates in water-stable aggregates and soil aggregate stability at three Nigerian locations (Abakiliki, Nsukka and Umudike) where forests had been converted to arable farming. The effect of management practices to enhance aggregate stability was site-specific. The highest aggregate stability was obtained with *Gliricidia sepium* at Abakiliki, with *Cajanus cajan* followed by rice mill wastes (RW) at Nsukka and with the forested soil at Umudike. While none of the treatments at all sites was able to enhance the C and N contents of the soils to the levels obtained in the forested sites, a net improvement in carbohydrate and organic carbon (OC) content was found for some management practices. The carbohydrate status increased with *G. sepium* at Abakiliki, and with *Dactylodenae bacterii* alone or in combination with *Pentaclethra* species at Umudike, while at Nsukka all organic inputs increased carbohydrate content over the control and forested soils. However, neither total OC nor the carbohydrate content were significantly correlated to the variability in aggregate stability of these soils. The δ^{13}C values found for acidic hydrolysates were constant within the soil aggregate sizes and generally distributed around −29 to −30‰, suggesting that the OC from these sites originated from C3 plants. Our results indicate that in these tropical Nigerian soils, aggregate stability and OC content are generally preserved by alley-cropping in well structured soil, whereas treatments with organic wastes are sustainable management practices in more fragile soils.

Keywords: Nigeria; Organic matter dynamics; Humus; Water-stable aggregates; Management practices; Isotopic δ^{13}C‰ values

1. Introduction

In the humid tropics organic matter is a major resource that links the chemical, physical and biological properties of soils (Andreux, 1996). It is a major indicator of soil quality since it is directly involved in the maintenance of soil fertility, prevention of erosion and desert encroachment and provision of suitable environment for biological activity (Zech and Guggenberger, 1996; Piccolo, 1996). According to Schlesinger (1997), organic matter is an important driving force in environmental global change as it acts as both a source and sink of atmospheric carbon. Different pools of soil organic matter (SOM), with varying stability and turnover rates, have been identified (Angers and N'Dayegamiye, 1991). Carbohydrates and humic substances can be considered as models for the labile and stable fraction of the organic carbon (OC) pool, respectively (Spaccini et al., 2000a,b).

* Corresponding author. Tel.: +39-081-7885239;
fax: +39-081-7755130.
E-mail address: alpiccol@unina.it (A. Piccolo).

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The massive deforestation and intensive cultivation taking place in the humid tropics (Lal, 1986) has led to loss of soil productivity due mainly to reduction in SOM. Soil carbohydrates, which represent from 5 to 25% of SOM (Stevenson, 1994), constitute a significant part of the labile pool of SOM and are most affected by land use changes (Guggenberger et al., 1995). Large emphasis had been given to the action of polymeric carbohydrates in stabilising soil structure (Chesire, 1979; Tisdall and Oades, 1982; Tisdall and Waters, 1991). However, due to the temporary biological stability of carbohydrates (Insam, 1996), their long-lasting role in improving soil physical properties may not be assumed in all soil conditions (Piccolo, 1996; Degens and Sparling, 1996; Piccolo and Mbagwu, 1999). Rhizosphere activity produces root exudates, mucilages and extracellular gums that may act as temporary cementing agents in the stabilisation of soil aggregates (Guggenberger et al., 1999; Tisdall and Oades, 1982), thereby providing protection against their destruction during the heavy rains of tropical climates. However, while the effects of land use reflect more on these labile carbohydrates than on the more stable, recalcitrant humic substances (Piccolo, 1996; Veldkamp, 1994), an evaluation of carbohydrates dynamics following cultivation of previously forested soils is still lacking in the tropical regions.

Results of studies in other regions of the world (Kaiser and Zech, 1999; Roberson et al., 1991; Arshad et al., 1990) suggest that the quality and quantity of carbohydrates in soils are influenced by factors such as: intensity of cultivation, soil type and texture, original soil carbon status and quality, distribution of natural aggregates in soils, and the ambient climate. In Nigeria, Mbagwu and Piccolo (1998) observed that soil carbohydrate content decreased with decreasing wet-aggregate size in the humid south, whereas Adamu et al. (1997) noted that with dry-aggregates the opposite was the case in the cool plateau of the north.

Apart from reports of reductions in soil aggregate stability and their relationship to SOM content when land is cultivated after deforestation, there is no detailed study in the tropics on the dynamics of carbohydrates and their distribution in different aggregate size fractions. With few exceptions (Beare et al., 1994; Elliott, 1986; Six et al., 1999, 2000; Pulleman et al., 2000), most studies of carbohydrates in temperate regions have generally considered bulk soil (<2.0 mm). However, understanding and modelling of SOM dynamics could improve if carbohydrate distribution in aggregate size fractions were known. Several authors (Davidson and Eckerman, 1993; Arrouays and Pelissier, 1994; Amelung et al., 1999; Shang and Tiessen, 2000) have already noted that more regional data are needed on the influence of soil texture, climate, soil types and land use on SOM dynamics when forests are cleared for arable cropping. To this aim, the variation of the $^{13}C/^{12}C$ ratio in carbohydrates passing from a forested to a cultivated soil may be useful to indicate the plant type from which the soil C originates (Boutton, 1996; Balesdent and Mariotti, 1996).

We determined soil C, N, C/N, ^{13}C abundance and carbohydrates in three Nigerian forest soils that had been converted to arable lands with and without organic inputs. Distribution of these properties in water-stable aggregate fractions was also determined.

2. Materials and methods

2.1. Soils, characteristics and experimental design

Geographical information on the three locations in Nigeria were given in detail by Spaccini et al. (2001), whereas clay mineralogy, soil classification, and some of the soil physico-chemical properties for each location are given in Table 1. The clay fraction was obtained by slow sedimentation in water after destruction of SOM with Na-hypochlorite. The X-ray diffractograms were obtained on oriented clay samples saturated with glycerol or $MgCl_2$. Clay mineralogy was performed on X-ray diffractometer using a Siemens D 500 diffractometer with Cu Kα radiation.

The experimental plots belong to the University of Nigeria and had been deforested in the 1970s using mechanical energy followed-up by hand hoeing. Small forest plots were conserved near-by (<1 km) and consisted of local rainforest species. The experiments for this study were set up continuously since 1990 (Abakiliki and Umudike) and 1991 (Nsukka) as a randomised complete block design with three replications for each treatment, one of which, the control was under arable cropping without further inputs of organic and inorganic fertilisers. Each plot was 5 m × 4 m in size. At Abakiliki the treatments were: (i) forested soil (F), (ii) control soil (under maize, *Zea mays* L.) without

Table 1
Location, classification, physical and chemical properties, organic C (OC), clay mineralogy and classification of some Nigerian soils

Location	Classification (USDA)	Sand ($g\,kg^{-1}$)	Silt ($g\,kg^{-1}$)	Clay ($g\,kg^{-1}$)	OC ($g\,kg^{-1}$)	pH (1:2.5 H_2O)	TEB[a] (Cmol(+)/kg)	CEC (Cmol(+)/kg)	Clay mineralogy[b]
Abakiliki: 06°30′N, 08°15′E	Inceptisol	540	200	260	24.0	5.59	16.4	34.5	M^{+++}; K^{++}; S^{+}
Nsukka: 06°51′E, 07°24′E	Ultisol	740	40	220	12.0	3.53	0.99	15.0	K^{+++}
Umudike: 05°29′N, 07°33′E	Ultisol	660	60	280	23.6	4.21	6.93	24.0	K^{+++}

[a] Total exchangeable bases.
[b] M: mica; K: kaolinite; S: smectite; +++: abundant; ++: present; +: few.

organic wastes additions (C), (iii) surface (0–20 cm) soil incorporated with leaves and twigs of *Leucenea leucocephala* (LL) and (iv) surface (0–20 cm) soil incorporated with leaves and twigs of *Gliricidia sepium* (GS). The rate of incorporation of each of these agro-forestry species was 20 t/ha per year of dry matter. At Nsukka the treatments were: (i) forested soil (F), (ii) control soil (under upland rice, *Oryza sativa*) without organic wastes additions (C), (iii) soil left at fallow with only *Cajanus cajan* (CC), (iv) surface soil (0–20 cm) incorporated with 20 t/ha poultry manure (PM), (v) surface soil (0–20 cm) incorporated with 20 t/ha rice mill waste (RW), (vi) surface soil (0–20 cm) incorporated with PM + RW at 10 t/ha each, and (vii) surface soil (0–20 cm) incorporated with 30 t/ha cow dung (CD). At Umudike the treatments were: (i) forested soil (F), (ii) control soil (under maize) without organic wastes additions (C), (iii) soil alley-cropped with *Dactylodenaea baterii* (Db), and (iv) soil alley-cropped with a mixture of *D. baterii* and *Penthaclethra* species (Db + P). These alley crops shed their leaves during the dry season, so they were not pruned. These are some of the dominant practices used to improve soil productivity in southern Nigeria. In all soils, incorporation of organic inputs was performed at plowing. At Abakiliki and Nsukka, cultivation consisted essentially of hand hoeing and planting without weed control, fertiliser addition and mechanical tillage. At Umudike mechanical cultivation (disking, ploughing and harrowing at about 20 cm depth) was used.

In the Fall of 1995, three bulked topsoil (0–20 cm) samples were collected with a spade from each replicate of treatments, air-dried, sieved through 4.75 mm mesh, and shipped to Italy for determination of distribution of water-stable aggregates, aggregate stability, carbohydrates in acid-hydrolysates of water-stable aggregates, elemental (C and N) composition and isotopic $\delta^{13}C$ contents in acid-hydrolysates of water-stable aggregates.

The <2 mm (fine earth from the <4.75 mm bulk sample) fraction was used to determine texture (with sodium hexametaphosphate as dispersing agent) by the pipette method of Gee and Bauder (1986). Soil pH was measured in 1:2.5 soil–water ratio, OC by the wet oxidation procedure of Nelson and Sommers (1982), exchangeable bases by the NH_4-acetate extraction technique and CEC by the procedure outlined by Anderson and Ingram (1993). The acid-hydrolysable carbohydrate content was measured in the water-stable aggregates by the phenol-sulphuric acid method described below. The C and N content in soil aggregate fractions were determined with a Fyson Elemental Analyzer on about 30 mg of sample weighed in small tin cups and values based on analytical duplicates. All determinations were made on each of the replicated samples.

2.2. Water-stable aggregates and aggregate stability

The procedure described by Kemper and Rosenau (1986) was used to separate the water-stable aggregates. Twenty grams of the <4.75 mm, air-dried soil samples 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 second. 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, C and N, and computation of C/N ratios. The percentage ratio of the aggregates in each sieve represents the water-stable aggregates of size classes: 4.75–1.00, 1.00–0.50, 0.50–0.25 and <0.25 mm. Mean-weight diameter (MWD) of water-stable aggregates was calculated as

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

where X_i is the mean diameter of the ith sieve size and W_i the proportion of the total aggregates in the ith fraction.

2.3. Acid-hydrolysable carbohydrates

The content of acid-hydrolysable carbohydrates in water-stable aggregates was determined in duplicate per sample using the phenol-sulphuric acid procedure (Piccolo et al., 1996). One gram of aggregate fraction was hydrolysed by shaking with 10 ml of a 0.25 M H_2SO_4 solution for 16 h in a rotary shaker. The interfering ions in the hydrolysate were reduced by elution through anion and cation exchange resins. The monosaccharide content in the hydrolysates was measured colorimetrically as glucose equivalents. All measurements were expressed as glucose concentration in g kg^{-1} of water-stable aggregates.

2.4. Elemental content and isotopic abundance ($\delta^{13}C$)

The C and N contents in water-stable aggregates and hydrolysates were measured using the Interscience EA1108 elemental analyser. Isotopic abundance (δ^{13}C) in the freeze-dried hydrolysates was measured by continuous-flow isotope ratio-mass spectrometry (Carlo Erba N Analyser 1500 coupled with Finnigan MAT 251, Bremen, Germany). The results of ^{13}C/^{12}C ratios were expressed in the relative δ scale (‰) according to the following equation:

$$\delta^{13}\mathrm{C‰} = \left(\frac{R_{\mathrm{sample}}}{R_{\mathrm{standard}}} - 1\right) \times 10^3$$

where $R = {}^{13}\mathrm{C}/{}^{12}\mathrm{C}$ and the standard is the Pee Dee Belemnite.

2.5. Statistical analysis

Simple correlation between MWD and soil organic C or acid-hydrolysable carbohydrates was used to evaluate their possible contribution to soil structural stability. For each location an analysis of variance was used to compare the effects of treatments on the measured properties. Where the F-values were significant at $P = 0.05$, the least significant difference (LSD) was calculated and used to separate significance among means.

3. Results

3.1. Effects of management practices on aggregate stability and organic matter content

At Abakiliki, all treatments had >50% water-stable aggregates in the 4.75–1.00 mm size (Table 2). At Nsukka and Umudike the reverse was the case with the 4.75–1.00 mm aggregate fractions varying from about 5–28% at Nsukka and 5–20% at Umudike.

The MWD values (Table 2) generally decreased from forested to control sites in all soils, while treatments had variable effects on MWD. Fallowing with *C. cajan* and incorporation of rice mill waste at Nsukka significantly improved the MWD values of treated soils above control values, while the soil under *G. sepium* significantly increased MWD value over control at Abakiliki. Rice mill wastes were previously noted (Mbagwu, 1989), at short periods of time (approximately 3 years), to increase MWD of the treated soils. No treatment was able to restore the MWD value of the forested soil at Umudike.

At each location, soil OC was greatest in the forested soil (Table 2). The restorative treatments acted differently in enhancing levels of SOM. For example at Abakiliki neither LL nor GS restored the OC level above the control value. At Nsukka this was significantly achieved with PM amendment, whereas at Umudike the alley-cropping of Db or Db + P reached OC levels significantly above the control values.

Notwithstanding the improvements in OC content, the correlation with MWD (an index of soil aggregate stability) for the corresponding treatments was either not significant or negative (Table 3).

Table 2
Percent distribution of water-stable aggregates (mm), mean-weight diameter (MWD) of size-aggregates, and organic C (OC) content in three Nigerian soils

Treatments[a]	Aggregate size distribution[b] (mm)				MWD (%)	OC ($g\,kg^{-1}$)
	4.75–1.00	1.00–0.50	0.50–0.25	<0.25		
Abakiliki						
F	63.0 a	13.6 c	7.4 d	16.0 b	1.95	24.0
C	59.2 a	9.0 c	6.1 d	25.7 b	1.81	10.4
LL	52.8 a	6.0 d	10.6 c	30.6 b	1.63	12.0
GS	70.1 a	19.3 b	6.3 c	4.3 c	2.18	7.6
LSD (0.05)	5.0	5.8	2.9	6.8	0.18	1.9
Nsukka						
F	14.7 c	33.2 a	26.7 b	25.4 b	0.77	12.0
C	5.8 c	36.4 a	37.9 a	19.9 b	0.56	6.7
CC	25.6 c	30.2 b	34.0 a	10.2 d	1.06	6.0
PM	20.8 c	32.9 b	35.8 a	10.5 d	0.95	9.9
RW	28.6 c	30.0 b	38.9 a	2.5 d	1.15	8.0
PM + RW	7.6 c	38.2 a	40.4 a	13.8 b	0.62	5.9
CD	9.4 d	40.3 a	34.2 b	16.1 c	0.68	5.6
LSD (0.05)	6.3	7.1	4.1	5.6	0.16	1.6
Umudike						
F	19.8 c	37.8 a	19.1 c	23.3 b	0.93	13.6
C	8.8 d	58.1 a	15.8 c	17.3 b	0.71	5.6
Db	5.0 d	38.5 b	46.5 a	10.0 c	0.56	8.8
Db + P	10.3 d	30.1 b	37.0 a	22.6 c	0.64	8.4
LSD (0.05)	4.2	6.6	5.2	6.0	0.11	2.1

[a] F: forested; C: control; LL: *L. luecocephala*; GS: *G. sepium*; CC: *C. cajan*; PM: poultry manure; RW: rice mill waste; CD: cow dung; Db: *D. bacterii*; P: *Pentaclethra* species.
[b] Different small letters in rows indicate significant difference at 0.05 probability level ($n = 3$).

3.2. Carbohydrate distribution in water-stable aggregates

In comparison to the forested soils at Abakiliki and Umudike, there was a reduction in the content of acid-hydrolysable carbohydrates in control soils and for all aggregate sizes (Table 4). At Nsukka such reduction was significant only in the >1 and <0.25 mm aggregate fraction. In the Abakiliki soil, with the highest MWD values, the carbohydrates measured in the <0.25 mm aggregates were larger than only the 4.75–1.00 mm fractions, whereas in the Nsukka and Umudike soils the carbohydrate concentrations were generally higher in the micro-aggregates (<0.25 mm) than in each of the macro-aggregates. Considering the unfractionated soils, the carbohydrate values were largest in the forested treatments at Abakiliki (32 $g\,kg^{-1}$) and Umudike (9 $g\,kg^{-1}$). At Nsukka, the treatments improved the carbohydrates content above the forested and control levels (Table 4). The largest improvement was obtained with cow dung (17 $g\,kg^{-1}$) followed by poultry manure + rice mill waste (15 $g\,kg^{-1}$) and fallowing with *C. cajan* (15 $g\,kg^{-1}$). A positive relationship between MWD

Table 3
Linear relationships between MWD and organic carbon (OC), and carbohydrate (RCHO) content of some Nigerian soils

Location	*N*	Regression equation	R^2	*P*
Abakiliki	12	MWD = 2.01 − 0.08 (OC)	0.294	*
Nsukka	21	MWD = 0.93 − 0.20 (OC)	0.598	**
Umudike	12	MWD = 0.63 − 0.04 (OC)	0.086	NS[a]
Abakiliki	12	MWD = 1.67 + 0.02 (RCHO)	0.044	NS
Nsukka	21	MWD = 0.54 + 0.03 (RCHO)	0.081	NS
Umudike	12	MWD = 0.45 + 0.15 (RCHO)	0.669	**

[a] Not significant.
* Significant at $P < 0.05$.
** Significant at $P < 0.01$.

Table 4
Distribution of carbohydrates (g kg^{-1}) in aggregate size classes of some Nigerian soils

Treatments[a]	Aggregate size classes (mm)[b]				Unfractionated bulk soil
	4.75–1.00	1.00–0.50	0.50–0.25	<0.25	
Abakiliki					
F	5.3 c	10.0 a	9.2 a	8.2 b	32.6
C	4.5 c	7.1 a	7.3 a	5.8 b	24.8
LL	7.4 a	6.9 a	5.5 b	4.7 b	24.4
GS	5.7 c	7.9 a	6.4 b	5.0 c	25.1
LSD (0.05)	0.7	0.9	0.9	1.0	5.5
Nsukka					
F	2.0 b	1.9 b	1.8 b	3.5 a	9.2
C	1.0 a	2.0 a	1.7 a	1.9 a	6.7
CC	3.2 b	4.0 a	3.3 b	4.5 a	15.1
PM	3.9 a	3.1 b	3.3 b	3.4 b	13.7
RW	3.0 a	3.3 a	2.9 a	3.1 a	12.3
PM + RW	3.9 b	3.6 c	2.9 c	5.0a	15.5
CD	5.3 a	3.1 b	3.9 b	5.1 a	17.4
LSD (0.05)	0.5	0.7	0.5	0.8	3.2
Umudike					
F	3.5 a	1.9 b	1.9 b	2.0 b	9.3
C	0.8 a	0.9 a	0.8 a	1.0 a	3.5
Db	0.9 b	1.1 b	1.3 b	1.5 a	4.9
Db + P	1.4 b	1.2 b	1.2 b	1.7 a	5.6
LSD (0.05)	0.5	0.4	0.4	0.3	1.0

[a] F: forested; C: control; LL: *L. luecocephala*; GS: *G. sepium*; CC: *C. cajan*; PM: poultry manure; RW: rice mill waste; CD: cow dung; Db: *D. bacterii*; P: *Pentaclethra* species.
[b] Different small letters in rows indicate significant difference at 0.05 probability level ($n = 3$).

and carbohydrates was significant only at Umudike, explaining 67% of variation.

3.3. Carbon and nitrogen concentration and $\delta^{13}C$ of aggregate fractions

The distribution of C, N, and C/N ratios of the aggregate fractions are shown in Table 5. In the Abakiliki soil, there was an increase in C and N as the aggregate sizes decreased in the forested soil. This may be possibly attributed to the high silt fraction of this soil (Table 1) that may have enriched in C and N the aggregates of smaller size in comparison to those of larger size. In the cultivated control and the soils alley-cropped with *Leucenea luecocephala* and *G. sepium*, the 0.50–0.25 mm aggregate fraction contained the highest amount of C and N. The larger size-aggregates as those >1.00 mm generally contained less C and N than the smaller aggregates (<1.00 mm) in all treatments for this soil.

In the Nsukka and Umudike soils the >1.00 and <0.25 mm aggregate fractions preferentially accumulated C and N relative to the other fractions. Also in these soils, the largest aggregates (>1.00 mm) accumulated less C and N than the smaller aggregates (<1.00 mm) irrespective of the treatments employed, except for the PM + RW treatment at Nsukka. Hence it is possible to infer that both C and N are sequestered in the micro-aggregates of these soils where they may be protected by a mechanism of incorporation into the hydrophobic domains present in the finest fractions (Piccolo and Mbagwu, 1999). However, in none of the sites the C and N levels of the forested soils were re-established by the management practices adopted for the cropped soils (Table 5). At Abakiliki, alley-cropping with *L. luecocephala* improved the C and N levels beyond those of the control, whereas alley-cropping with *G. sepium* did not achieve the same result. Also at Umudike alley-cropping with *Dactylodenae bacterii* or *D. bacterii* + *Pentaclethra*

Table 5
Carbon and nitrogen content ($g\,kg^{-1}$), and C/N ratios in aggregate sizes of some Nigerian soils

Treatments[a]	Aggregate size distribution (mm)											
	4.75–1.00			1.00–0.50			0.50–0.25			<0.25		
	C	N	C/N	C	N	C/N	C	N	C/N	C	N	C/N
Abakiliki												
F	1.6	0.17	9.8	3.9	0.30	13.3	4.3	0.33	13.1	7.0	0.48	14.7
C	1.1	0.09	11.9	2.3	0.18	13.3	2.9	0.22	13.4	2.4	0.17	13.9
LL	1.2	0.10	12.2	2.1	0.16	13.3	3.1	0.23	13.4	2.8	0.21	13.4
GS	1.0	0.09	11.6	1.6	0.13	12.7	1.9	0.15	12.7	1.7	0.14	12.5
LSD (0.05)	0.1	0.01	0.6	0.1	0.01	0.8	0.1	0.01	0.6	0.1	0.02	0.7
Nsukka												
F	2.2	0.17	13.2	0.8	0.06	13.8	0.8	0.06	12.7	1.5	0.12	12.9
C	1.4	0.08	17.7	0.7	0.05	16.3	0.7	0.05	15.7	0.9	0.06	15.1
CC	1.3	0.11	12.1	0.6	0.05	12.6	0.6	0.05	12.3	1.1	0.09	12.8
PM	1.4	0.10	14.4	0.9	0.06	15.2	0.5	0.03	14.6	1.1	0.08	13.5
RW	1.5	0.09	15.6	0.4	0.03	13.7	0.4	0.03	11.5	1.0	0.09	10.9
PM + RW	2.2	0.23	9.5	0.7	0.07	9.6	0.6	0.06	10.8	1.0	0.09	11.1
CD	1.8	0.13	13.8	0.7	0.06	11.2	0.7	0.06	11.2	0.6	0.07	8.6
LSD (0.05)	0.1	0.02	0.6	0.1	0.01	0.6	0.1	0.01	0.8	0.1	0.01	0.9
Umudike												
F	5.3	0.45	11.8	2.6	0.22	12.0	2.1	0.17	12.3	2.1	0.18	11.7
C	1.5	0.12	13.4	0.5	0.03	15.3	0.4	0.04	11.6	1.1	0.08	13.9
Db	2.4	0.14	17.0	1.1	0.08	14.0	0.6	0.04	13.0	1.3	0.10	14.0
Db + P	2.5	0.17	14.8	0.7	0.06	13.3	0.6	0.05	13.0	1.4	0.11	13.1
LSD (0.05)	0.1	0.02	0.9	0.1	0.01	1.3	0.1	0.01	0.7	0.1	0.01	1.0

[a] F: forested; C: control; LL: *L. luecocephala*; GS: *G. sepium*; CC: *C. cajan*; PM: poultry manure; RW: rice mill waste; CD: cow dung; Db: *D. bacterii*; P: *Pentaclethra* species.

species improved C and N far above the control level. At Nsukka, similar results were found for the poultry manure, poultry manure + rice mill waste, and cow dung practices which out-performed the control sample. The C/N ratios of all aggregate fractions were generally within the levels expected for most soils.

The C, N, and C/N ratios for the freeze-dried hydrolysates of the aggregate classes are given in Table 6. With few exceptions, the values for C, N and C/N ratio did not vary substantially in the carbohydrate extracts from the different aggregate sizes. However, some differences were noted among the soils. For example, in the Abakiliki soil the >1.00 mm aggregate size showed less C and N content than the intermediate sizes (1.00–0.50 and 0.5–0.25 mm), while the values for <0.25 mm fraction were again similar to those of the >1.00 mm size. Moreover, at Abakiliki no management practice was able to improve the C and N to the levels of the forested soil in the >1.00 and <0.25 mm fractions, whereas the 1.00–0.50 mm size showed a significant increase of values. At Nsukka the differences among all treatments were not substantial, except for the CC treatment that revealed a significant increase of C content in the >1.00 mm fraction and a decrease in the 1.00–0.50 mm size-aggregate. At Umudike, the C and N values for the control were significantly larger than the forested values in both the >1.00 and <0.25 mm fractions, while the *D. baterii* alley-cropping was effective in enhancing these values in respect to the forested site in all aggregate size and the treatment with *D. bacterii* + *Pentaclethra* species showed instead a decrease of C content in the >0.5 mm fractions.

Results from the isotopic $\delta^{13}C$ values in the hydrolysates from aggregate-size fractions are also given in Table 6. These values were intended for assessing the origin of OC between that of the former vegetation (forest, savannah and pasture) and that of cultivation and use of different kinds of organic amendments. However, the $\delta^{13}C$ values were generally constant

Table 6
Elemental C and N content (g kg^{-1}), C/N ratio, and δ^{13}C (‰) in hydrolysates from aggregate size classes of some Nigerian soils[a]

Treatments	Aggregate size distribution (mm)															
	4.75–1.00				1.00–0.50				0.50–0.25				<0.25			
	C	N	C/N	δ^{13}C	C	N	C/N	δ^{13}C	C	N	C/N	δ^{13}C	C	N	C/N	δ^{13}C
Abakiliki																
F	3.1	0.75	4.1	−29.97	1.2	0.30	4.2	−28.67	2.3	0.54	4.3	−30.15	2.0	0.48	4.2	−30.03
C	1.6	0.38	4.4	−29.91	2.3	0.54	4.3	−30.29	2.2	0.50	4.4	−30.46	1.9	0.44	4.4	−30.06
LL	1.7	0.40	4.2	−29.94	2.3	0.53	4.3	−30.29	2.1	0.48	4.3	−30.34	1.5	0.36	4.2	−29.67
GS	2.0	0.48	4.1	−29.91	2.1	0.52	4.0	−29.97	1.7	0.43	4.0	−29.64	1.7	0.42	4.1	−29.64
LSD (0.05)	0.1	0.03	0.2	0.15	0.1	0.02	0.1	0.16	0.1	0.03	0.1	0.11	0.1	0.04	0.1	0.14
Nsukka																
F	2.3	0.52	4.4	−29.99	2.5	0.75	3.4	−30.25	2.4	0.55	4.3	−30.41	2.2	0.48	4.7	−30.12
C	2.3	0.52	4.5	−29.86	2.4	0.55	4.3	−29.85	2.1	0.49	4.3	−30.07	2.1	0.49	4.3	−29.78
CC	3.6	0.26	13.8	−23.08	1.6	0.37	4.4	−30.14	2.2	0.54	4.2	−30.36	2.3	0.50	4.5	−29.81
PM	2.1	0.46	4.6	−29.57	2.4	0.54	4.5	−29.69	2.5	0.56	4.4	−29.98	2.0	0.45	4.5	−29.53
RW	2.3	0.49	4.6	−29.79	2.4	0.54	4.4	−29.68	2.3	0.53	4.4	−30.31	2.2	0.49	4.5	−29.95
PM + RW	2.4	0.55	4.3	−29.86	2.4	0.55	4.4	−30.05	2.5	0.59	4.2	−30.34	2.0	0.47	4.3	−29.46
CD	2.3	0.54	4.3	−30.77	2.3	0.55	4.2	−30.31	2.3	0.54	4.2	−30.51	2.6	0.63	4.2	−30.40
LSD (0.05)	0.1	0.05	0.2	0.13	0.1	0.05	0.1	0.17	0.1	0.05	0.1	0.14	0.1	0.04	0.1	0.19
Umudike																
F	2.1	0.54	3.8	−27.55	2.1	0.69	3.1	−27.61	2.1	0.66	3.3	−27.89	1.8	0.56	3.2	−27.69
C	6.7	1.44	4.6	−25.62	2.3	0.28	8.3	−21.79	2.1	0.58	3.6	−30.23	2.5	0.76	3.3	−30.03
Db	2.7	0.86	3.2	−30.11	2.6	0.80	3.3	−30.40	2.3	0.71	3.2	−29.97	2.0	0.60	3.4	−29.75
Db + P	2.2	0.67	3.3	−29.68	2.5	0.67	3.7	−29.91	0.9	0.21	4.2	−28.63	0.8	0.20	4.2	−28.98
LSD (0.05)	0.1	0.08	0.1	0.21	0.1	0.07	0.1	0.12	0.1	0.04	0.1	0.17	0.1	0.06	0.1	0.15

[a] F: forested; C: control; LL: *L. luecocephala*; GS: *G. sepium*; CC: *C. cajan*; PM: poultry manure; RW: rice mill waste; CD: cow dung; Db: *D. bacterii*; P: *Pentaclethra* species.

within the aggregate size fractions and they were mostly distributed around −30‰. Two exceptions are noteworthy here. The first is at the Umudike site (rainforest vegetation) for the four different size fractions of the forested soil where δ^{13}C values were around −27.7‰ and for the >1.00 and 1.00–0.50 mm fractions of the control treatment which showed −25.6 and −21.8‰, respectively. The second case is where *C. cajan* was used as soil amendment in Nsukka and showed a value around −23‰ for the extract coming from the >1.00 mm size fraction. The rest of treatments did not show a significant effect for soil and applied crop management systems.

4. Discussion

The SOM quality and dynamics in terrestrial ecosystems influences the aggregate stability in soils according to their mineralogy (Six et al., 2000; Denef et al., 2002). Spaccini et al. (2001) observed that OC and acid-hydrolysable carbohydrates were reduced when tropical forested soils were cultivated and that neither of these constituents accounted for the differences in the aggregate stability of soils. These results were partially confirmed in this study where just a poor correlation ($R^2 = 0.67$) between carbohydrates content and aggregate stability (MWD) was found only for the Umudike soil. This supports other findings suggesting that polysaccharides cannot be always considered as persistent structural stabilisers because of their rapid degradation by microbial activity (Angers and Mehuys, 1989; Insam, 1996; Piccolo and Mbagwu, 1999). In fact, a decrease in carbohydrate concentration in all aggregate sizes in the control treatments compared with the forested sites was observed at Abakiliki and Umudike but not at Nsukka (Table 4). However, the adopted waste management techniques were in some cases successful in increasing the carbohydrate content over that of control soil. An increase was found with alley-cropping, using *D. bacterii* either alone or in combination with *Pentaclethra* species at Umudike, while at Nsukka, with the lowest aggregate stability, intercropping with *C. cajan* and addition of rice mill waste and poultry manure also showed an increase of carbohydrate content. Only a slight increase in carbohydrate content was observed in the Abakiliki soil as a result of treatments.

The respective textural characteristics of soils may account for these results. The high aggregate stability of the Abakiliki soil provided a relatively high carbohydrate content even in the control treatment. This favourable condition allowed, with the alley-cropping treatments, a slight increase in carbohydrates only in larger aggregate sizes (1.0–0.50 mm), where the products deriving from initial decomposition of plant residues tend to accumulate (Guggenberger et al., 1995). The different treatments strongly affected the carbohydrate content in soils with low silt and clay content, especially the Nsukka soils, where both the forest and control samples had the lowest aggregate stability. With the exception of *D. bacterii*, all other alley crops were legumes that have the advantage of low C/N ratios and rapid mineralisation, once incorporated in the soil (Fernandes et al., 1997). Moreover, Scholes et al. (1997) reported that the use of *L. luecocephala* contributed organic N to soils and plants but did not significantly increase either SOM content or biomass C content.

It is possible to infer from this study that the increase in carbohydrate and SOM concentrations (which are readily available to microbes in aggregate sizes) of the alley-cropped soils is a function of the soil physical properties. The high silt and clay content may influence the formation of both micro- and macro-aggregates when cementing agents such as carbohydrates are released in soils during OM degradation (Oades, 1984). According to Feller and Beare (1997), OC content in tropical soils is associated with the fine-silt + coarse-clay content. Since the quantity of these textural fractions occurred more in the Abakiliki than other soils, it is conceivable that carbohydrates were more physically protected against microbial degradation by these reactive particles (Chesire and Hayes, 1990; Piccolo, 1996). This is in line with other work (Angers and Mehuys, 1989; Caron et al., 1992) where the presence of biologically stable carbohydrates in soil aggregates did not influence aggregate stability.

Others (Guggenberger et al., 1995; Hu et al., 1995; Zech and Guggenberger, 1996; Zena et al., 1998) have observed that, for many tropical and temperate soils, carbohydrates in micro-aggregates and sand-sized particles were mainly due to decomposition of plant residues, whereas microbially derived sugars accounted for a larger proportion in clay-sized micro-aggregates. The higher carbohydrates concentration in the finer aggregates of the alley-cropped treatments at both Abakiliki and Umudike and of the poultry manure and rice mill waste treatments at Nsukka, may thus be related to an improved microbial activity because of the easily decomposable legume residues and fresh OM rather than accumulation of OC from plant residues.

In soils with lower physical quality, a general and significant increase in carbohydrates was found in micro-aggregates ($<$0.25 mm). In this aggregate size fraction, the presence of a high content of humified OM controls the biological stabilisation of carbohydrates in that they may become protected from microbial degradation by incorporation into the less polar domain of stable OM such as humic substances (Piccolo, 1996; Spaccini et al., 2001). The elemental (C and N) composition and the C/N ratios of these treatments followed the same trend as that of carbohydrates concentrations and may again be explained by a mechanism of increased physical (Oades, 1984) and chemical (Piccolo, 1996) protection of OM.

Isotopic analyses in the freeze-dried hydrolysates from the water-stable aggregates indicated that the hydolysable OM originated from C3 plant species. The δ^{13}C values in soil hydrolysates (from -22 to -32) are all within the range of isotopic values found in this study (-28 to -30) and characteristic of carbohydrates derived from plants with a C3 photosynthetic pathway (Boutton, 1996; Balesdent and Mariotti, 1996). The variability in δ^{13}C values shown among soil hydrolysates of forested and cultivated soils in these locations could also be attributed to the different ^{13}C–OC content of natural and cultivated C3 plant species which form the vegetation cover in the various sites.

At each location the respective treatments did not alter this trend. At Abakiliki, the forest consisted mainly of *Gmelina arborea*, whereas the alley crops were *L. leucocephala* and *G. sepium* which are C3 plants. Also at Umudike the alley crops are C3 plant species. At Nsukka, the forests are C3 plants but the duration of the amendments at the sites was lower, hence the OM from the original C3 vegetation manifested in this study.

In conclusion these results provide additional information on the behaviour of OM during soil management with organic inputs in tropical conditions. In the more structurally stable soil (Abakiliki) carbohydrates and elemental C and N were more evenly distributed in the size-aggregates, whereas they preferentially accumulated in the smallest (<0.25 mm) aggregates and in the >1.00 mm fraction in the less stable Nsukka and Umudike soils. When carbohydrate are stored in the micro-aggregate fraction they are protected from microbial degradation as a result of physical and chemical (such as hydrophobic interactions) processes (Piccolo and Mbagwu, 1999; Piccolo et al., 1999; Spaccini et al., 2000a). The isotopic $\delta^{13}C$ values of soil hydrolysates were generally similar and suggested that the OC derived predominantly from plants with C3 photosynthetic pathway. A beneficial effect of management practices in preserving the soil aggregate stability as well as the OM content was shown by the alley-cropping system with *L. luecocephala*, *G. sepium*, and *D. bacterii* in the more structured soils, whereas the more fragile soil was preserved mainly by amendments with organic wastes such as rice residues and poultry manure.

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