Soil & Tillage Research 60 (2001) 135–142

www.elsevier.com/locate/still

Structural stability and carbohydrate contents of an ultisol under different management systems

J.K. Adesodun[a], J.S.C. Mbagwu[a,*,1], N. Oti[b]

[a]Department of Soil Science, University of Nigeria, Nsukka, Nigeria
[b]Department of Crop Production, Federal University of Technology, Owerri, Nigeria

Received 4 April 2000; accepted 9 February 2001

Abstract

An understanding of the dynamics of soil carbohydrate pools is necessary for assessing the impact of organic residue management in organic matter build up and structural stability in tropical ecosystems. The objectives of this study were to evaluate temporal changes in aggregate stability and cold water-soluble, hot water-soluble and acid-soluble carbohydrate fractions of a sandy soil under different organic residue management practices. The soil is an Nkpologu sandy clay loam (fine-loamy, kaolinitic, isohyperthermic, typic kandiustult) at Nsukka in southeastern Nigeria. In July 1995, it was incorporated with complete fertiliser (N:P:K = 12:12:17 at 480 kg/ha) (F); rice mill wastes (RW, 10 t/ha); RW + F; poultry manure (PM, 10 t/ha) and RW (5 t/ha) + PM (5 t/ha) up to the 0–20 cm depth. A control, tilled up to the 0–20 cm depth, was also included. Surface soil samples (0–20 cm), collected at 3, 6 and 12 months after residue applications were used to measure changes in aggregate stability by mean weight diameter (MWD), total OC and carbohydrate pools.

In all treatments MWD increased whereas the concentrations of acid-soluble, hot water-soluble and cold water-soluble carbohydrates decreased with sampling time. Also irrespective of the type of amendment, the carbohydrate concentrations at each sampling period varied in the order, acid-soluble $>$ hot water-soluble $>$ cold water-soluble. Aggregate stability correlated very poorly with all the carbohydrate fractions and OC. The correlation coefficient values were rather low and did not mean much in the physical interpretation of these results. This shows that these carbohydrate pools were not very effective in stabilizing the soil aggregates. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Aggregate stability; Soil organic matter pools; Carbohydrate concentrations; Soil management practices

1. Introduction

The structural stability of a soil has an impact on a wide range of processes that influence crop growth, soil erosion, runoff and the transport of contaminants from farmlands to surface water bodies (Ketcheson, 1980; Perfect et al., 1990). Information on the form and persistence of the aggregating constituents of soil organic matter (SOM) is vital, particularly when dealing with fragile tropical soils which are exposed to high risk of water erosion.

Considerable controversy exists from studies carried out in temperate regions on the actual role of organic matter in soil aggregate stability. Some workers (Hamblin and Greenland, 1977; Dormaar, 1983) reported that it is the fractions of organic matter rather than the amount per se that are important in modifying the structural stability of aggregates whereas others

---

[*] Corresponding author.
E-mail address: misunn@aol.com (J.S.C. Mbagwu).
[1] Tel.: +234-42-770568; fax: +234-42-771977.

PII: S0167-1987(01)00164-7

(Chaney and Swift, 1984; Christensen, 1986) found a direct correlation between total SOM content and aggregate stability.

There are also differences of opinion regarding the actual fractions of OM that are responsible for improving soil aggregation. In recent years, the carbohydrate fraction of SOM has received considerable attention because it is as important as glues (Oades, 1984). Differences in results may be related to the source of carbohydrates and the residence time of the organic materials producing them in the soil. The objectives of this study were (1) to evaluate the comparative effectiveness of organic and inorganic amendments in stabilizing soil aggregates and (2) to assess the role of the carbohydrate fractions from the organic materials in aggregate stability.

2. Materials and methods

2.1. The study area

This study was conducted in the University of Nigeria, Nsukka, teaching and research farm (06°52′N, 07°24′E). The area is characterized by a tropical climate with marked wet and dry seasons and a mean annual rainfall of about 1700 mm. The soil is deep, well-drained and red to brownish-red in color and derived from sandy deposits of false-bedded sandstone (Orajaka, 1975). It is a sandy clay loam and classified as typic kandiustult in soil taxonomy (Nwadialo, 1989; Soil Survey Staff, 1986) which is equivalent to Dystric Nitisol in the FAO classification (FAO/UNESCO, 1988).

2.2. Field methods

A land area of 0.0876 ha was used for the experiment. The experimental design was the randomized complete block design (RCBD) with six treatments each replicated four times giving a total of 24 plots. The treatments were applied as follows:

1. control — no amendment (C);
2. complete fertilizer (F), N:P:K = 12:12:17 at 480 kg/ha;
3. rice mill waste (RW) at 10 t/ha;
4. RW + F;
5. poultry manure (PM) at 10 t/ha;
6. PM (5 t/ha) + RW (5 t/ha).

All the amendments were applied in a single dose in July 1995 when cassava was also planted.

At 3, 6 and 12 months after application of the amendments (i.e., October 1995, January and July 1996, respectively), six soil samples were collected randomly from 0 to 20 cm depth of each plot and bulked together to obtain a composite sample before air-drying and sieving to obtain the <4.75 mm aggregates which is used to determine aggregate stability and the carbohydrate pools. Also at the initiation of the study, the <2.0 mm soil fraction was used for routine characterization of the soil in terms of texture, pH, OC, total N, total exchangeable bases, cation exchange capacity and exchangeable sodium percentage (Table 1) by the procedures outlined in Page et al. (1982). The RW and PM were also analyzed for acid-soluble carbohydrates, humic substances, carbon mineralization constant, OC and total N (Table 2).

Table 1
Some properties of the top (0–20 cm) of the experimental soil

Parameters	Units	Values
Sand (2000-50 μm)	g/kg	700
Silt (50-2 μm)	g/kg	20
Clay (<2 μm)	g/kg	280
Texture	–	Sandy clay loam
pH (H_2O)	–	5.02
OC	g/kg	6.8
Total N	g/kg	0.87
C:N	–	7.8
Total exchangeable bases	Cmol/kg	4.27
CEC	Cmol/kg	14.5
ESP	%	5.9

Table 2
Some characteristics of the organic wastes used

Parameter	RW	PM
OC (g/kg)	321.1	229.4
Total N (g/kg)	7.3	28.6
C:N	44.0	8.0
Humic substances (HS) (g/kg OM)	485	786
Total carbohydrates (g/kg OM)	44.7	81.9
Carbon mineralization constant (per day)	0.00189	0.00297

2.3. Laboratory studies

2.3.1. Measurement of aggregate stability

The distribution of aggregates was estimated by the wet-sieving technique described in detail by Kemper and Rosenau (1986). In this procedure, 40 g of the <4.75 mm aggregates were placed on the topmost of a nest of sieves of diameters 2, 1, 0.5 and 0.25 mm, and pre-soaked in distilled water for 10 min before oscillating vertically in water 20 times (along a 4 cm amplitude) at the rate of 1 oscillation/s. The resistant aggregates on each sieve were dried at 105°C for 24 h, weighed and corrected for the sand fraction to obtain the proportion of the true aggregates. The mass of <0.25 mm fraction was obtained by difference. The percent water-stable aggregates (WSA) in each of the following size ranges, 4.75–2.0, 2.0–1.0, 1.0–0.50, 0.50–0.25 and <0.25 mm were then determined. Thus,

$$\mathrm{WSA} = \left[\frac{M_{\mathrm{a+s}} - M_{\mathrm{s}}}{M_{\mathrm{t}} - M_{\mathrm{s}}}\right] \times 100 \qquad (1)$$

where $M_{\mathrm{a+s}}$ is the mass of the resistant aggregates plus sand (g), M_{s} the mass of the sand fraction alone (g) and M_{t} the total mass of the sieved soil (g).

The method of Van Bavel (1950) as modified by Kemper and Rosenau (1986) was used to determine the mean weight diameter of the water-stable aggregates. Thus,

$$\mathrm{MWD} = \sum_{i=1}^{n} X_i W_i \qquad (2)$$

where MWD is the mean-weight diameter of water stable aggregates, X_i the mean diameter of each size fraction (mm) and W_i the proportion of the total sample weight (WSA) in the corresponding size fraction, after deducting the weight of stones (upon dispersion and passing through the same sieve) as indicated above.

2.3.2. Measurement of carbohydrate contents

The carbohydrate fractions in the whole-soil samples (<4.75 mm fraction) were determined in duplicate in three types of soil extracts, viz. dilute acid-soluble, hot water-soluble and cold water-soluble as follows:

1. 1 g of soil was mixed with 10 ml of 0.25 M H_2SO_4 and shaken in a plane rotary shaking machine for 16 h;
2. 1 g of soil was mixed with 10 ml of hot distilled water (85°C) and heated for 2.50 h;
3. 1 g of soil was mixed with 10 ml of cold 25°C, distilled water and shaken in a plane rotary shaker for 16 h.

All the three types of soil suspension were centrifuged at 3000 rpm for 30 min. After centrifugation, 2 ml of the supernatant solution were used to determine the carbohydrate concentration using the phenol–sulfuric acid method of Dubois et al. (1956). The absorbency was read in a spectrophotometer (Jouan Model VP 10.12) at 490 nm. The calibration curve was obtained using glucose standard.

2.3.3. Data analysis

To evaluate the influence of these carbohydrate pools on aggregate stability, simple correlation analysis (Little and Hills, 1972) of the measured fractions with MWD was done. Also an analysis of variance (ANOVA) for a randomized complete block design (RCBD) was used to evaluate the effects of the amendments on the measured soil properties; where the *F*-tests were significant, the Duncan's multiple range test was used to separate the mean values.

3. Results and discussions

3.1. Effect of amendments on aggregate stability

The MWD increased with time in all treatments (Table 3). At 3 months, PM gave the highest improvement of 23% over the control which decreased to 5% at 12 months. At 6 months, RW + F gave a relative improvement of 15% but at 12 months, it decreased below the control value. At 12 months, RW gave 15% improvement over the control. The order of highest relative improvement in MWD is PM (at 3 months), RW + F (at 6 months) and RW (at 12 months). Hence PM with low C:N acted fast whereas RW with high C:N was slow in acting as an aggregating agent.

With the exception of the 12th month values from RW + F and RW + PM treated-plots, the amendments generally increased the MWD over the control.

Table 3
Aggregate stability (MWD) of the experimental soil treated with organic and inorganic fertilisers[a]

Months after application	Treatments						
	C	F	RW	RW + F	PM	RW + PM	Means
3	0.759	0.862	0.787	0.762	0.931	0.854	0.826
6	1.095	1.115	1.229	1.261	1.227	1.257	1.197
12	1.271	1.367	1.456	1.253	1.336	1.113	1.299
Means	1.042	1.115	1.157	1.092	1.165	1.057	–

[a] LSD = 0.05, treatments (T) = 0.152, months (M) = 0.319 and T × M = 0.223.

There was a differential performance of these amendments with time. Here, after 3 months of incorporation, all the amendments improved aggregate stability with PM giving the highest improvement. On the average, at the 3rd month, the order of improvement in aggregate stability was PM > F > RW + PM > RW > RW + F > C (Table 3). Six months after, the amendments maintained their positive aggregation influence with RW + F giving the highest improvement. The order of improvement at this period was RW + F > RW + PM > RW > PM > F > C. At the 12th month, RW gave the highest improvement on aggregate stability, and the order of improvement was RW > F > PM > C > RW + F > RW + PM. This study showed that, over a longer period, RW gave a better improvement in aggregate stability, while mixtures of RW + F, PM + RW and PM improved aggregate stability over shorter periods (Table 3).

The decrease in improvement of aggregate stability observed in RW + F and RW + PM treated-plots at the 12th month relative to the 6th month may be due to further mineralization of the highly fibrous RW with high C:N, leading to increased CO_2 evolution and loss of OC. There is a content of OC above which there is no further increase in water-stable aggregation (Tisdall and Oades, 1982) due to the increase in the negative charge on colloid surfaces favoring dispersion. Mbagwu (1992a,b) observed that addition of F and PM to RW increased the rate of mineralization of the RW. The improvement in aggregate stability with time in the control plots could be partially explained by microbial processes.

3.2. Concentration of carbohydrate pools

There was a differential performance of the amendments in terms of their contribution to carbohydrate concentrations in the soil. The general trend of the acid-soluble carbohydrate concentrations shown in Table 4 indicates a general decrease in this carbohydrate fraction from the 3rd to the 12th month irrespective of the amendment used. Considering the mean values, there was a reduction of 41.3% in this carbohydrate fraction between the 3rd and the 12th months. At the 3rd month, all the organic amendments maintained higher levels of the acid-soluble carbohydrates

Table 4
Changes in dilute acid-soluble carbohydrates (mg/kg) of the experimental soil as influenced by type of amendment and time of sampling[a]

Months after application	Treatments						
	C	F	RW	RW + F	PM	RW + PM	Means
3	342	443	649	612	625	627	550
6	315	330	341	547	588	616	456
12	304	316	334	314	324	347	323
Means	320	363	441	491	512	530	–

[a] LSD = 0.05, treatments (T) = 27.8, months (M) = 76.2 and T × M = NS.

Table 5
Changes in hot water-soluble carbohydrates (mg/kg) of the experimental soil as influenced by type of amendment and time of sampling[a]

Months after application	Treatments						
	C	F	RW	RW + F	PM	RW + PM	Means
3	196	207	248	217	222	234	221
6	171	175	208	177	194	201	188
12	141	146	198	157	162	167	162
Means	196	176	218	184	193	201	–

[a] LSD = 0.05, treatments (T) = 20.2, months (M) = 25.4 and T × M = NS.

more than the inorganic fertilizer and the control plots. Among the treatments, this acid-soluble carbohydrates ranged in value from 342 (in the control plot) to 649 mg/kg (in the RW-amended plots) in the 3rd month, from 315 (in the control plots) to 616 mg/kg (in the combined RW and PM-amended plots) in the 6th month and from 304 (in the control plots) to 347 mg/kg (in the RW + PM-amended plots) in the 12th month.

Between the 3rd and 12th months, there was a significant $(P = 0.05)$ decrease in the acid-soluble carbohydrates concentrations across all the treatments. The absolute decreases were 11% (control), 29% (F), and between 45 and 49% (for the organic amendments).

The values of the hot water-soluble carbohydrates shown in Table 5 were 2–3 times lower than those of the acid-soluble carbohydrates. As with the acid-soluble carbohydrates fraction this hot water-soluble fraction also decreased significantly $(P = 0.05)$ with time of sampling. On the average there was a decrease of 26.7% in this fraction between the 3rd and 12th months which is much lower than the 41.3% decrease in the acid-soluble fraction as indicated above. Also at each sampling time the control plot had the lowest values which did not significantly differ from the values in the F-plots. However, at the 3rd month of sampling, all the hot water-soluble carbohydrate fractions were significantly $(P = 0.05)$ higher than the values in the control and F-plots. The decrease in this fraction of carbohydrates between the 3rd and 12th months varied between 20.2% in the RW plots and 29.5% in the F-plots.

The fraction with the lowest values are the cold water-soluble carbohydrates (Table 6). With respect to the time of sampling, with the exception of the F plot there were generally no significant differences in this fraction between the 3rd and 12th months. Also with respect to the amendments, it was only the 6th and 12th months' cold water-soluble carbohydrate fractions for the RW plots that differed significantly $(P = 0.05)$ from the control values. Again as with the hot water-soluble carbohydrates, the highest values in this fraction were obtained in the RW plot with the lowest values obtained in the control plots. On the average, this cold water-soluble carbohydrate

Table 6
Changes in cold water-soluble carbohydrates (mg/kg) of the experimental soil as influenced by type of amendment and time of sampling[a]

Months after application	Treatments						
	C	F	RW	RW + F	PM	RW + PM	Means
3	37	44	55	41	47	49	46
6	31	34	51	39	44	47	41
12	28	30	48	36	43	45	38
Means	32	36	51	39	45	47	–

[a] LSD = 0.05, treatments (T) = 18.5, months (M) = 9.7 and T × M = NS.

Table 7
Changes in organic carbon (g/kg) of the experimental soil as influenced by type of amendment and time of sampling[a]

Months after application	Treatments						
	C	F	RW	RW + F	PM	RW + PM	Means
3	6.7	10.0	11.1	10.7	9.6	10.4	9.8
6	6.5	8.6	9.7	9.0	8.5	9.5	8.6
12	6.2	7.4	7.3	8.6	7.7	8.3	7.6
Means	6.5	8.7	9.4	9.4	8.6	9.4	–

[a] LSD = 0.05, treatments (T) = 0.381, months (M) = 0.649 and T × M = NS.

fraction decreased by 17.4% from the 3rd to the 12th months. Higher percent decreases were obtained in the control and F plots (24.3–31.8%) than in the organic wastes amended plots (8.3–12.7%).

3.3. Changes in total organic carbon concentrations

As with all the three carbohydrates concentrations measured, the OC concentrations also decreased with time of sampling (Table 7). Generally OC was highest at 3 months (6.7–11.1 g/kg), followed by 6 months (6.5–9.7 g/kg) and least at 12 months (6.2–8.6 g/kg). On the average, the control treatment had low OC values, whereas relatively high OC values were recorded in the F, PM, RW, RW + F and RW + PM treatments. This is also a reflection of the C:N of the amendments with the RW-treated plots having lower mineralization rate (0.00189 per day) and hence higher OC than the PM- and F-treated plots. The decrease in the control plot OC concentrations between the 3rd and 12th months was 3%. With respect to the amendments, the highest decrease in OC was obtained in the RW plot (34.2%) whereas the lowest decreases were obtained in the RW + F (19.6%) and PM (19.8%) plots.

3.4. Correlation of organic carbon and carbohydrate pools with aggregate stability

We correlated MWD of water-stable aggregates with the total OC, acid-soluble, hot water-soluble and cold water-soluble carbohydrates obtained throughout all the three sampling periods because we wanted to assess the roles of OC and these carbohydrate fractions in aggregate stability. From our discussions above, whereas the MWD increased with sampling time, the concentrations of OC, acid-soluble, hot water-soluble and cold water-soluble carbohydrates decreased with time. Consequently the results presented in Table 8 showed consistently that both the OC and carbohydrate fractions correlated negatively but significantly ($P = 0.05$) with MWD. The exception to this is the non-significant correlation between MWD and cold water-soluble carbohydrates. The correlation coefficient values are low (probably because of the 1 year study) and may not mean much in the physical interpretation of these results but they point to the fact that both the OC and the carbohydrate fractions were not contributing to aggregate stabilization of the soil particles.

Several authors have attributed the poor correlation between MWD and organic carbon fractions to the transient nature of the polysaccharides in soils. Even though Chaney and Swift (1986), Angers and Mehuys (1989), Haynes and Swift (1990) and Angers et al. (1993) showed that amendment of aggregates with glucose produced stable aggregates, Insam (1996) insisted that since carbohydrates are easily degraded by microorganisms, they cannot participate in long-term stabilization of soil aggregates. The implication

Table 8
Relationship between organic matter pools and aggregate stability

Regression equations	Coefficient of determination (r^2)
MWD = 1.780 – 0.078 (OC)	0.258*
MWD = 1.450 – 0.001 (CHO-dilute acid)	0.234*
MWD = 2.052 – 0.005 (CHO-hot water)	0.440*
MWD = 1.419 – 0.007 (CHO-cold water)	0.065[a]

[a] Not significant.

* Significant at $P = 0.05$.

of this is that other binding agents are involved in aggregate stabilization.

The short-term effect of polysaccharides on soil aggregate stability was recently confirmed by Piccolo and Mbagwu (1999). Also Dutarte et al. (1993) associated aggregate stability with the humified organic matter fractions in sandy soils from West Africa. Earlier studies by Piccolo and Mbagwu (1990) and Mbagwu and Piccolo (1998) also reported a significantly positive correlation between micro-aggregate stability and humic acid content than either the total OC or the carbohydrate content. Carbohydrates participate in aggregate stabilization when they act in conjuction with the more humified soil organic matter pools (Angers and Mehuys, 1989; Caron et al., 1992; Piccolo and Mbagwu, 1999). Hence simply isolating carbohydrates alone and testing statistically their effect on aggregate stability appears to indicate low and sometimes negative relationships as observed in this study.

In conclusion the amendments applied improved aggregate stability with time whereas the concentrations of OC and carbohydrate pools decreased with time. The correlation between aggregate stability and these carbohydrate fractions were low, albeit negative, and shows that these fractions were not contributing to structural stability in this soil.

Acknowledgements

The authors are grateful to the European Union for a grant used in financing this study under the European Union STD Project titled “Stability of Organic Matter Pools in African (Nigeria and Ethiopia) Ecosystems.

References

Angers, D.A., Mehuys, G.R., 1989. Effects of cropping on carbohydrate content and water-stable aggregation of a clay soil. Can. J. Soil Sci. 69, 373–380.

Angers, D.A., Samson, N., Lègére, A., 1993. Changes in water-stable aggregation induced by rotation and tillage in a soil under barley production. Can. J. Soil Sci. 73, 51–59.

Caron, J., Kay, B.D., Stone, J.A., 1992. Improvement of structural stability of a clay loam with drying. Soil Sci. Soc. Am. J. 56, 1583–1590.

Chaney, K., Swift, R.S., 1984. The influence of organic matter on aggregate stability in some British soils. J. Soil Sci. 35, 223–230.

Chaney, K., Swift, R.S., 1986. Studies on aggregate stability. 2. The effect of humic substances on the stability of reformed soil aggregates. J. Soil Sci. 37, 337–343.

Christensen, B.T., 1986. Straw incorporation and soil organic matter in macroaggregates and particle size separates. J. Soil Sci. 36, 219–229.

Dormaar, J.F., 1983. Chemical properties of soil and water-stable aggregates after 67 years of cropping of spring wheat. Plant Soil 75, 51–61.

Dubois, M., Gilles, K.A., Hamilton, J.K., Rebers, P.A., Smith, F., 1956. Colorimetric method of determination of sugars and related substances. Analyt. Chem. 28, 350–356.

Dutarte, P., Bartoli, F., Andreaux, F., Portal, J.M., Ange, A., 1993. Influence of content and nature of organic matter on the structure of some sandy soils from West Africa. Geoderma 56, 459–478.

FAO/UNESCO, 1988. Soil Map of the World. Revised Legend. UNESCO, Paris.

Hamblin, A.P., Greenland, D.J., 1977. Effect of organic constituents and complexed metal ions on aggregate stability of some east Anglian soils. J. Soil Sci. 28, 410–416.

Haynes, R.J., Swift, R.S., 1990. Stability of soil aggregates in relation to organic constituents and soil water content. J. Soil Sci. 41, 73–83.

Kemper, W.D., Rosenau, K., 1986. Size distribution of aggregates. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1. ASA, Madison, WI, pp. 425–442.

Insam, H., 1996. Microorganism and humus in soils. In: Piccolo, A. (Ed.), Humic Substances in Terrestrial Ecosystems. Elsevier, Amsterdam, pp. 265–292.

Ketcheson, J., 1980. Long-range effects of intensive cultivation and monoculture on the quality of southern Ontario soils. Can. J. Soil Sci. 60, 403–410.

Little, T.M., Hills, F.J., 1972. Statistical Methods in Agricultural Research. University of California, Davis, CA, 242 pp.

Mbagwu, J.S.C., 1992a. Improving the productivity of a degraded Ultisol in Nigeria using organic and inorganic amendments. Part 1. Chemical properties and maize yield. Bioresource Technol. 42, 149–154.

Mbagwu, J.S.C., 1992b. Improving the productivity of a degraded Ultisol in Nigeria using organic and inorganic amendments. Part 2. Changes in physical properties. Bioresource Technol. 42, 167–175.

Mbagwu, J.S.C., Piccolo, A., 1998. Water-dispersible clay in aggregates of forest and cultivated soils in southern Nigeria in relation to organic matter constituents. In: Bergstrom, L., Kirchman, H. (Eds.), Carbon and Nutrient Dynamics in Natural and Agricultural Ecosystems. CAB International, Wallingford, UK, pp. 71–83.

Nwadialo, B.E., 1989. Soil landscape relationship in Udi-Nsukka plateau, Nigeria. Catena 16, 111–120.

Oades, J.M., 1984. Soil organic matter and structural stability: mechanisms and implication for management. Plant Soil 70, 319–337.

Orajaka, S.O., 1975. “Geology”. In: Ofomata, G.E.K. (Ed.), Nigeria in Maps: Eastern States. Ethiope Publishing House, Benin, Nigeria.

Page, A.L., Miller, R.H., Keeney, D.R., 1982. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. ASA, Madison, WI.

Perfect, E., Kay, B.D., Vanloon, W.K.P., Sheard, R.W., Pojasok, T., 1990. Rates of change in soil structural stability under forages and corn. Soil Sci. Bok. Am. J. 54, 179–186.

Piccolo, A., Mbagwu, J.S.C., 1990. Effects of different organic amendments on soil aggregates stability and molecular sizes of humic substances. Plant Soil 123, 27–37.

Piccolo, A., Mbagwu, J.S.C., 1999. Role of hydrophobic components of soil organic matter in soil aggregate stability. Soil Sci. Soc. Am. J. 63, 1801–1810.

Soil Survey Staff, 1986. National Soil Taxonomy Handbook No. 8, Part 615. Amendment to Soil Taxonomy. USDA-SCS. US Government Printing Office, Washington, DC.

Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33, 141–163.

Van Bavel, C.H.M., 1950. Mean-weight diameter of soil aggregates as a statistical index of aggregation. Soil Sci. Soc. Am. Proc. 14, 20–23.