Soil structure stability and the organic system in heavy montmorillonite clays

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The results of analyses from the experiment Station at Sainte-Anne, Martinique, F.W.I., on Vertisols, emphasize the importance of nitrogen compounds in the formation of humic substances and in the development of a stable structure under an alternate sorghum cultivation. The carbon–nitrogen interaction suggests the existence of a characteristic organization of the organic system. Such organization can be used for a better efficiency of farming systems.

Keywords: Clay soils; Soil structure; Organic matter; Montmorillonite

Intensive cultivation of irrigated Vertisols is confronted with difficulties, due to physical changes (degradation of soil structure, hardening or cementing) or to chemical changes or development of diseases. The improvement of such soils, rich in montmorillonite clays, depends largely on various factors, among which organic matter plays an important role: for example, organic compounds act effectively on cation exchange capacity, water retention and the formation and stabilization of soil structure. The work of many researchers clearly demonstrates that the formation and stabilization of soil aggregates is a function of the nature and configuration of organic compounds. Polysaccharides (microbial gums) or carbohydrates are among the organic compounds most often cited. Polysaccharides seem to act so efficiently that the effect of organic matter on soil structure is virtually attributed to these compounds (Greenland *et al.*, 1962). The polycondensation phenomena of humic compounds are also involved in the development of soil structure: due to the abundance of functional groups (hydroxyl, carboxyl, amine), (Harris *et al.*, 1966 in Allison, 1973) or to molecular weight changes (Dell'Agnola and Ferrari, 1971). In a general sense, the bonding between organic polymers and montmorillonite is well demonstrated in the laboratory.

In the field, the organic matter–clay association reveals itself as a complex material, susceptible to rapid change. The organization of a stable organo-mineral complex is usually understood as a global result accounted for by multiple factor interactions. Here, differences in soil structure which are illustrated by an alternate sorghum cultivation on an irrigated Vertisol are considered. The dynamics of humification are analysed and emphasize the importance of the carbon–nitrogen interaction in the formation and maintenance of a stable structure.

Materials and methods

Soils

The experiment station for irrigated Vertisols at Sainte-Anne, Martinique, is established on a Vertisol soil unit which predominates in the S.E. irrigated area. Its characteristics are presented in Table 1. The soil has clay texture and is weakly desaturated (79% sat.) with moderately acid pH 6. Aggregation – or structural stability – decreases with depth, the (B) horizon having a poor structural stability. The clay is montmorillonite and Ca–Mg are predominant as exchangeable cations, sodium is also present; the pH decreases rapidly when cultivation takes place and can reach a value of 4 following regular input of fertilizers, such as ammonium or potassium sulphate.

Climate

The total rainfall is variable (1973: 771.4mm, 1974: 1113 mm, 1975: 913.7mm) and long dry periods can be observed when sudden showers occur.

Evaporation from *Digitaria* sp. grassland reaches 1900 mm a year: the daily evaporation is ≈5-6 mm, during warm periods (March to September) but decrease to 4 mm a day in November, December and January. The mean annual water deficit is 700 mm. Irrigation is managed to compensate for the evapotranspiration loss and according to water needs at different vegetative periods.

Methods

Structure stability

Structure stability is determined by an aggregate analysis, submitted to three pretreatments (water, alcohol, benzene); stable and dispersed fractions are determined. An instability index (*Is*) (Henin *et al.*, 1960) can be calculated according to the following formula:

$$Is = \frac{(A + L)\ \text{max}}{Ag\ (\text{mean}) - 0.9\ SG}$$

where $(A + L)$ max represents the dispersed silt and clay ratio with the benzene pretreatment; Ag (mean) the aggregates and coarse sand betweeen 0.2 and 2 mm and SG, the mean value for coarse sand.

Structure stability is here estimated as the difference between moist soil cohesion and pressure in capillary tubes (Monnier, 1965), related to the absorptivity. For tropical soils an adequate instability index is ≈ 0.40; and a poor one higher than 1 (Boyer Combeau, 1970). When coarse sand is low (here, less than 5%), the aggregate ratio can be considered as a criterion of stability. The present paper uses interchangeably the instability index or the % aggregates.

Organic matter

On air-dry samples, total carbon is determined by the Walkley-Black method.

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Table 1 Vertisols - analytical data (Colmet-Daage *et al.*, 1967)

Depth cm	Hor.	Clay	Silt	Sand	C, ‰	N, ‰	C/N	Ca	Mg	K	Na	CEC	pH water
								Milliequivalents					
0–15	A	64	14	9.4	15.0	1.51	9.9	18.7	17.7	0.33	2.31	49	6.0
60–80	(B)	68	12	9.9	6.9	0.7	9.8	12.3	15.0	0.09	5.4	45	5.8

0–15cm; brown 10YR 3/2, large shrinkage cracks when dry, macro-structure in coarse blocks >10cm, micro-structure is polyhedric
15–80cm; yellow brown, structural (B) horizon with massive structure and cracks.

The organic matter is separated into two fractions: (*a*) a fraction extracted by a mixture (Na pyrophosphate 0.1 N, sodium hydroxide 0.1 M) (Kononova and Bel'chikova, 1970). The extraction is performed until soluble fractions are exhausted. (*b*) a non extracted fraction, residue or humin. Seventy per cent. of total carbon, called total humic matter or humic extract, can be extracted in this way. Fulvic acids and humic acids are separated by acidification of the solution.

Total nitrogen is determined by the Kjeldhal method. Nitrogen forms (hexosamine, *N*-amino-acids, *N*-ammonium) are obtained by acid hydrolysis (6N HCl) (Bremner, 1965); these forms represent the main part of hydrolysable N. The analysis concerns the total soil sample and the humin residue. The N forms of humic acid extract are obtained by difference.

Results

The analysis covered a wide range of field plots, with alternate sorghum cultivation, vegetables or sugar-cane.

Structure stability and soil moisture

The comparison between aggregate ratio and soil moisture at the time of sampling, clearly indicates that an optimum for aggregation exists at ≈ 23% of humidity (% wet soil) (Fig. 1). This optimum corresponds to the value of soil moisture given by the experiment station for optimum soil preparation (25% for ploughing, 22% for rotary hoeing) (Roux, personal communication).

Excessive dryness induces a decrease in the aggregates ratio and suggests the existence of a critical moisture value (Hartmann and De Boodt, 1974) corresponding to maximum aggregation for this type of soil. This value is within the values obtained for pF 3, near those for pF 4.2.

Humic acids and soil structure – soil structure evolution under alternate cultivation of sorghum

A positive relationship (Fig. 2) exists between humic acids carbon (C ‰.) and the aggregate ratio. Distribution of the data on the graph demonstrates three points: (*a*) ploughing during a wet period leads to a decrease in the level of humic acids and the aggregate ratio falls to a low value. (*b*) The effect of a soil preparation on the soil structure is effectively dependent on the moisture at the time of preparation. (*c*) Twelve months or more of sorghum cultivation leads to a high level of aggregates and humic acids in the surface horizon, i.e. sorghum modifies effectively the level of stable aggregates (Table 2). The aggregate ratio depends on the extent of cultivation, and the nature of irrigation.

The improvement after 12 months cultivation is as high again as when the cultivation is performed with irrigation. The thickness of the A 11 horizon affected by this improvement (Turenne, 1976), is as thick when the cultivation is older (6 cm after 2 months, 13 cm after 20 months) or irrigated (13 cm on irrigated plots, 9 cm on non-irrigated plots). The maximum development is reached after 18 months. Granier (1976) noticed also that sorghum plots dry more rapidly at the end of the rainy season, allowing an earlier soil preparation: measurement of soil moisture when sampling under the same conditions,

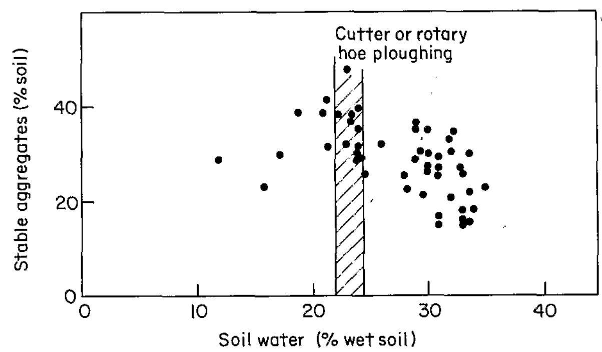

Fig. 1 Stable aggregates and field moisture

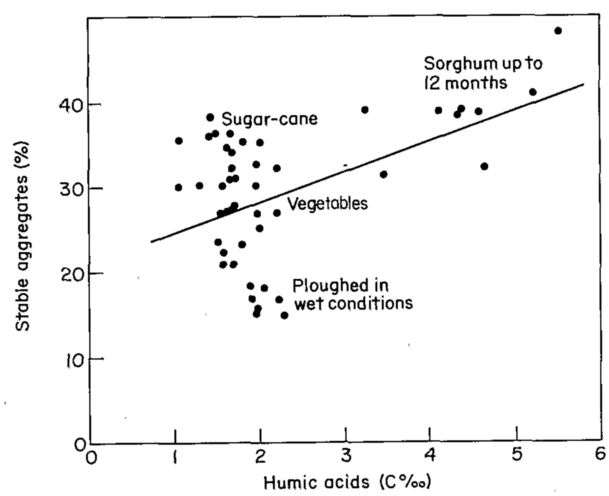

Fig. 2 Relation between humic acids and stable aggregates in Vertisols. Ag % = 21.43 + 3.42 C‰ AH. $n = 46$, $r = 0.45$

show also a lower retention for the oldest plots (Table 2).

The setting of vegetable cultivation after sorghum, induces (Table 3) a decrease of the aggregate ratio. This decrease depends on the preceding water regime for the sorghum (Table 2). A bad soil structure with the higher instability index is obtained at the end of the vegetable cultivation, for the plot with preceding irrigated sorghum: the irrigation of sorghum induces a more rapid and greater amelioration of the structure stability, which seems to be less resistant to degradation. However, the management of the sorghum cultivation, without irrigation promotes a better formation and stabilization of aggregates. The seasonal changes – wet and dry periods – to which this plot is naturally submitted, lead to a structure stability more resistant to degradation (Fig. 3).

Structure stability and aminated nitrogen forms

One notices (Fig. 4) the effect of aminated nitrogen (AN) on the soil structure: a low stability index corresponds to high quantities of aminated nitrogen: the structure stability is directly related to the aminated nitrogen present in the humic extract, the relation being:

$$Is = -1.198 \log_{10} \alpha\text{-AN (humus)} + 2.81, \; n = 27 \; r = 0.48$$

Organic matter dynamics

Results on organic matter change are present in Table 4 [carbon ratio, C; nitrogen, N; C/N ratio; humic acids ratio (HA/C); condensed or grey humic acids (GHA); CEC; aminated nitrogen (AN)]. The The αA nitrogen (Bremner, 1967) represents 10-60% of total nitrogen, up to 40% of this form may be contained in the humic extract and participates in this case, in the formation of condensed humic compounds.

Humification

A positive relationship exists between the humic ratio and the part of aminated nitrogen in the total nitrogen. The concentration of nitrogen forms is as high as the humic forms are abundant. This agrees with the observation of several authors (Sharpenseel and Kruse, 1972; Flaig, 1975) that the increase of the humic acids goes through an increase of aminated nitrogen forms (Fig. 5).

Structure stability and humification dynamics

A high stability is obtained for a high level of humic acids and for a high level of aminated nitrogen. The following equation is obtained:

$$\text{Aggregates \%} + 16.68 + 3.34\, C_{HA} \text{ ‰} + 10.31 \text{ total AN}, \; n = 34 \; r = 0.62.$$

During dynamic phases of amelioration, it is observed that the combination or interaction between carbon and nitrogen is of prime importance for the constitution of a stable structure. For instance (Fig. 6) sorghum cultivation within 2 months is marked by an increase of αA nitrogen (1), then by a combination or interaction of these nitrogen forms with the humic carbon (2) or by a simultaneous increase of the two forms (3–4) (5–6); this interaction is concurrent with high structural stability.

At the extreme, crop planting or ploughing in bad conditions induces a de-condensation of humic form and leads to poor structural stability with a low level of humic carbon and nitrogen (Figure 6). In the two cases (interaction or degradation of condensed humic forms) the path by transitory forms with a low degree of humic forms, and the presence of a high level of organic aminated nitrogen, are indicated.

Out of these temporary stages, the data follow a linear regression characteristic of the clay soil studied: this correlation suggests that the condensation of humic acids is not random but follows a characteristic combination in this environment. These transformations (Table 4) are developed without any significant variation in the total carbon level; it is not the quantity of total carbon present in the soil but the quality or, better, the organization which conditions soil structure.

Table 2 Soil structure variation with alternate sorghum cultivation

	Extent of cultivation (months)				
	2	10	15	20	24
Non-irrigated plots:					
Soil moisture, %	26.3	24.7	23.4	18.9	20.9
Aggregates, %	22.8	35.1	36.9	38.8	38.3
Is (instability index)	2.04	0.96	0.71	0.68	0.65
Irrigated plots:					
Soil moisture, %	26.3	21.3	22.2	23.4	22.9
Aggregates, %	22.8	41.4	38.7	38.4	47.8
Is (instability index)	2.04	0.49	0.68	0.85	0.57

Table 3 Vegetable cultivation and soil structure evolution

	Extent of cultivation (days)				
	0	24	49	100	135
Non-irrigated sorghum preceding:					
Aggregates %	38.33	24.48	31.9	29.95	28.86
Is	0.65	1.09	0.90	1.52*	1.17
Irrigated sorghum preceding:					
Aggregates %	47.8	35.6	40.8	24.0	35.4
Is	0.57	1.03	0.68	2.07	0.93

*End of vegetable and ploughing in dry season

Discussion and conclusions

Stable aggregation or soil structure stability depends on the interaction of organic compounds, i.e. humic chains and aminated nitrogen compounds. The development of stable structure is in fact dependent on several factors:

(1) The water regime: the existence of critical moisture conditions determines the agricultural practices, but rules also the organic dynamics. The alternations of dry and wet periods lead to a stronger

condensation of the humic compounds and the resulting aggregates in these conditions are more resistant to degradation. The introduction of alternating dry–wet periods in the irrigation regime has to be taken into account even in vegetable

Table 4 Effect of alternate sorghum cultivation on change in organic pool

	Extent of cultivation (months)				
	2	10	15	20	24
Non-irrigated plots:					
C ‰	16.8	14.6	16.4	14.5	16.0
N ‰	1.33	1.40	1.33	1.29	1.29
C/N	12	10.4	12.3	12.2	12.4
GHA % Grey (HA)	19.3	28.7	29.2	28.0	35.0
HA*	9.4	7.8	26	30	26
CEC	40	42	38	33	34
AN (aminated N)	0.460	0.672	0.630	0.580	0.546
Irrigated plots:					
C ‰	16.8	15.7	14.6	15.7	16.8
N ‰	1.33	1.26	1.33	1.36	1.75
C/N	12	12.5	11.0	11.5	9.6
GHA % Grey (HA)	19.3	25.8	27.7	23.6	31.6
HA*	9.4	33	22	29	33
CEC	40	37	33	32	34
AN (aminated N)	0.462	0.574	0.518	0.518	0.714

*Humic acid ratio (HA/total C)

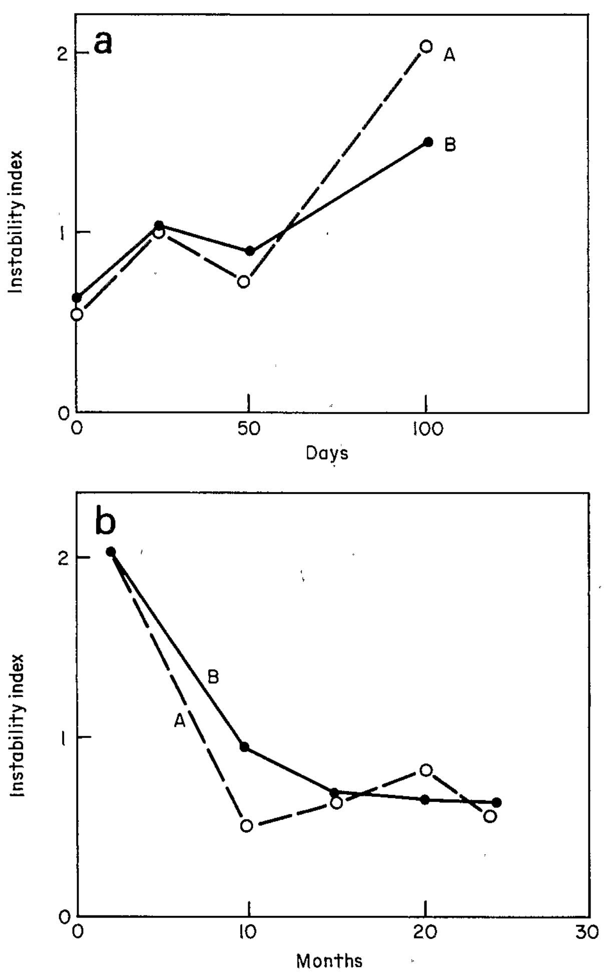

Fig. 3 Changes of instability index (*Is*) during cultivation. (a) Changes during an alternate sorghum cultivation. A, Irrigated; B, non-irrigated. (b) Changes during vegetable cultivation. A, after irrigated sorghum; B, after non-irrigated sorghum

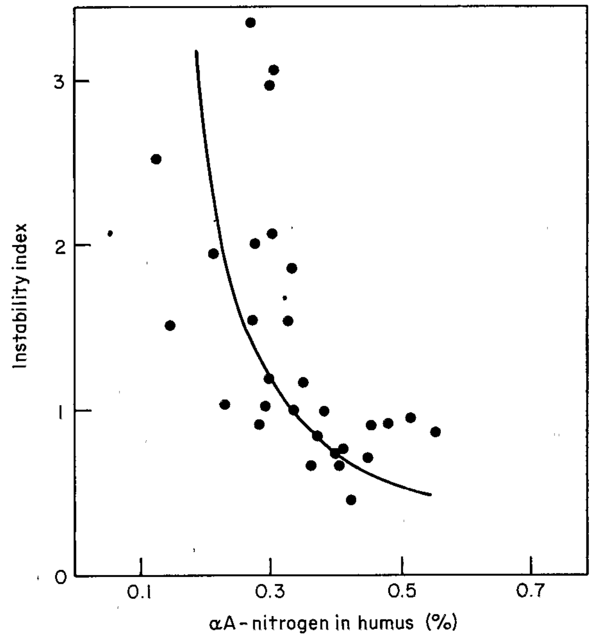

Fig. 4 Relation between instability index (*Is*) and α-AN in humus fraction

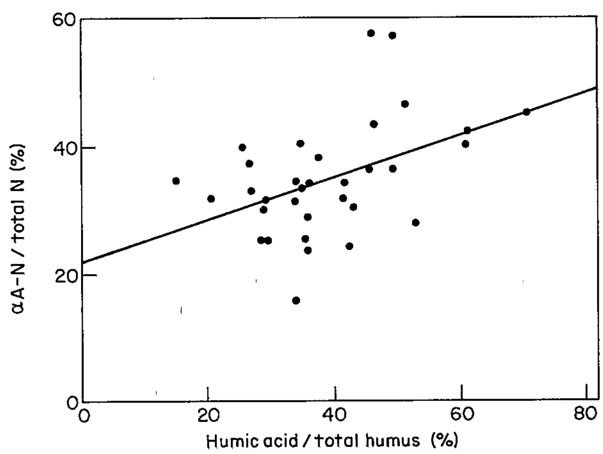

Fig. 5 Vertisols – relation between αA-nitrogen/total nitrogen and humic acid/total humus. $n = 36$, $r = 0.434$

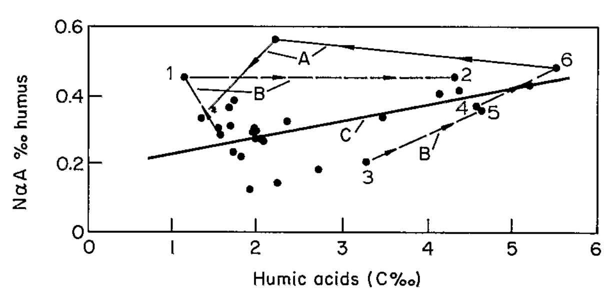

Fig. 6 Relation between humic acid (C ‰) and aminated nitrogen in the humus fraction. A, Changes during vegetable cultivation; B, changes during an alternating sorghum cultivation; C, high stability

cultivation, with harmonization of both plant water needs and maintenance of aggregate stability.

(2) The presence of aminated compounds and their combination in the humic chains with polycondensation of these chains: the level of stable aggregates varies with the aminated nitrogen and combined with humic acids. These transformations occur in almost all cases without any notable variation in the total carbon ratio. The quality of the organic matter is of prime importance in the evolution of the structure of montmorillonite clays. In this case, the aminated forms have a bonding function on the one hand between humic forms (Flaig *et al. op. cit.*) and on the other hand, between humic forms and mineral (Fripiat *et al.*, 1962).

(3) The relation which occurs between nitrogen and carbon, when considering humic forms: this suggests that the condensation of the organic does not occur at random but follows a characteristic rule in this montmorillonite clay.

The improvement of the Vertisols depends on an intensification of cultural practices tending to obtain a better interaction between humic compounds (carbon and nitrogen) and between organic compounds and mineral. An input of organic matter or more generally the management of cultural practices must aim at obtaining maximum efficiency of the humic compounds, simultaneously by a good distribution of these compounds in the mineral (Monnier, 1965) and by the maintenance of the carbon/nitrogen interaction in the humic chains at the highest level. The valorization of nitrogen compounds in such soils has to take into account the root effect, the irrigation regime, the period of agricultural practices and the input of pre-humified compounds.

Discussion

B.R. Cooper One of your diagrams showed an equally high level of soil structure after sugar-cane as after sorghum, but at a lower organic matter level. Is this correct and could you comment?

Author Your observation is correct. However, it is not at a lower organic matter level but at a lower level of humic acids in the organic matter, suggesting that other compounds in the soil are involved, e.g. polysaccharides, hexosomines, etc.

S.M. Griffith Are there changes in the base saturation per cent. or in the types of basic cations as the organic matter 'changes in quality?'

Author Exchangeable Mg and cation exchange capacity both decrease during the condensation of humic acids. The reduction in exchangeable Mg suggests that this cation is involved in the polycondensation phenomena.

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