Aggregation and Organic Matter Storage in Kaolinitic and Smectitic Tropical Soils

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I. Introduction

In most of the tropical regions, the clearing of native vegetation and the development of the land for food crop production, generally leads to drastic changes in soil properties. Decreases in plant nutrient reserves, organic matter (OM) and organic carbon (OC) contents, as well as a structure degradation are principally observed in low activity clay (LAC) soils, even those managed by low-intensified cultivation practices (Nye and Greenland, 1960; Fauck et al., 1969; Morel and Quantin, 1972; Siband, 1974; Sanchez, 1976; Feller and Milleville, 1977; Boyer, 1982; Moreau, 1983; Albrecht and Rangon, 1988; Pieri, 1989). The agronomic and ecological consequences are a decline in crop production and an increase in soil erodibility or soil erosion (Lal and Greenland, 1979; Roose, 1981).

Plant nutrient reserves can be relatively well-controlled by inputs of fertilizers and manures (Sanchez, 1976), but it is more difficult to manage soil physical properties and especially their structure in a long-term perspective. The stability of soil structure is a consequence of numerous interactive factors including crop rotations, cultural practices, soil OM content, and soil biological activities. Thus, the study of the relationships between soil structure and organic carbon storage in tropical agricultural soils represents one of the major aspects of soil fertility and conservation.

In this chapter we shall consider the above relationships through the following four points: (i) The general relationships between structure, cultivation and OC storage with some emphasis on macromorphological observations and statistical correlations; (ii) The distribution of OM and aggregates in the surface soil with some emphasis on particle size approaches; (iii) The role of OM in the 'stabilization' of structure, and (iv) The correlative role of soil structure in the 'stabilization' of soil OM throughout the physical protection effect against mineralization processes or against detachability, erodibility and transportability.

Because soils exhibit very different chemical and physical properties, especially in relation to their mineralogy, three main groups of tropical soils can be distinguished:

(i) The 'low activity clay (LAC) soils,' the clay minerals of which are dominated by 1:1 type phyllites, as kaolinites and halloysites, associated with more or less crystallised Fe, Al, Mn oxides and/or hydroxides. In this paper they will be termed 'LAC' soils or 'Kaolinitic' soils. In the US Soil Taxonomy they are mainly represented by alfisols, ultisols and oxisols and secondarily by some inceptisols and entisols. LAC soils cover about 60% of the tropical areas and more than 70%, if aridic and mountainous lands are excluded (after Sanchez, 1976);

(ii) The 'high activity clay (HAC) soils,' the clay minerals of which are dominated by 2:1 clay minerals as smectites. They are mainly represented by vertisols (about 3% of tropical areas);

(iii) The 'allophanic soils,' the mineral constituents of which are dominated by amorphous or crypto-crystallized minerals, as allophanes and imogolites. They are well represented by andisols which cover about 1% of tropical lands.

LAC soils principally and, more specifically, well-drained LAC soils will be considered in this paper. Some comparisons will be made with vertisols, but andisols will not be discussed.

II. General Considerations on Soil Structure and Aggregate Stability

Different definitions of soil structure have been proposed, either in a static and descriptive sense (five definitions reported by Jastrow and Miller, 1991), or in a more dynamic and functional way with references to soil management (Lal, 1979; Cassel and Lal, 1992). In the first case, soil structure is 'the arrangement of primary particles into aggregates' with various detailed descriptions of soil aggregates as they naturally occur in natural conditions. The nature and magnitude of forces acting between soils particles is generally invoked. For examples, 'In aggregates, forces holding the particles together are much stronger than those occurring between adjacent aggregates' (Martin et al., 1955, quoted by Robert and Chenu, 1992). In the second case, soil structure corresponds to 'those properties of soil that regulate and reflect a continuous array of various sizes of interconnected pores, their stability and durability, capacity to retain and transmit fluids and ability to supply water and nutrients for supporting active root growth and development' (Cassel and Lal, 1992). These conceptions were integrated by Dexter (1988) who defined soil structure as 'the spatial heterogeneity of different components or properties of soil.'

In relation to the functionality definition, Lal (1979) proposed various methods to evaluate soil structure and its stability: rainfall acceptance, aggregate stability, soil erodibility, detachability and transportability, porosity and pore-size distribution. Some of these different aspects will also be considered in this paper.

Physical fractionation techniques are a powerful approach to characterize the relationships between soil OM and aggregation on the macro- and microaggregate scales. Historically it is clear that size fractionation of macro- and microaggregates was an early and common method to evaluate both distribution and stability of soil aggregates (Kemper and Chepil, 1965; Henin et al., 1958). From 1970, both size and density fractionation methods, using wet sieving, were extensively used to separate soil OM forms. Detailed reviews concerning historical concepts, methodological aspects and applications to the study of bio-organomineral interactions in the soil were recently published (Elliott and Cambardella, 1991; Christensen, 1992; Feller, 1995). However, the aggregate size fractionation (AGSF) and the organic matter size fractionation (OMSF) are based on completely different approaches. For AGSF only low energy is generally involved to limit both disaggregation and dispersion of organomineral colloids. For OMSF, the main methodological objective is to reach a maximum soil dispersion, close to that obtained by mechanical analysis (Bremner and Genrich, 1990; Feller et al., 1991a; Christensen, 1992). The simultaneous use of these methods provide the means to separate quantitatively and with limited OM solubilisation, different compartments of OM, such as plant debris associated to sands, organo-silt complexes composed of particulate organic debris and very stable organomineral microaggregates, and organo-clay fractions enriched in amorphous and humified OM, partly having a microbial origin.

For organomineral interactions studies, the above two approaches appear to be very complementary: naturally occuring water stable aggregates may be separated by AGSF and their composition studied by OMSF. In view of this, Christensen (1992) termed the organo-clay fraction obtained by OMSF as a 'primary organomineral complex,' while the aggregates obtained by AGSF as the 'secondary organomineral complexes.'

At present, this double approach of AGSF and OMSF to characterize organomineral interactions is beginning to be widely applied to soils of cold or temperate regions (see previous chapters). By contrast, few published data are available for tropical situations. Therefore, in this paper some unpublished data obtained recently by the authors on a collection of soil surface samples originated from West Africa, Antilles and Brazil, will be presented. The samples were selected in order to test the effects of OM content, texture, mineralogy and cultivation on different soil properties.

III. Sites, Soils and Methods

A. Sites and Soils

The results reported here were obtained from the pedological situations summarized in Tables 1 and 2. For each situation comparisons were made between plots corresponding to different types of soil management. Most of the analytical data were summarized in Feller (1994) and are not detailed here.

Changes in soil properties will be studied as a function of: (i) Clearing of the native vegetation and of the duration of continuous cropping on sites 3, 5, 11 and 12; (ii) Spontaneous grass- or tree-fallows, and eventually their duration, on sites 1, 2, 3, 5, 6 and 10; (iii) Artificial meadows after continuous annual cropping on sites 7, 8 and 9; (iv) Organic amendments (crop residues and/or animal manures) on sites 1, 2, 3, 8, 9, 10. With exception of some plots at site 9, all sites chosen were apparently not eroded. Each soil sample (0-10, 10-20, 20-40 cm) was constituted from 6 to 12 replicates. The coefficients of variation of OC contents ranged from 3 to 18% with a mean value of 11%. The mean value of confidence interval was calculated to be 9%.

These soils belong to the following orders of the US Soil Taxonomy: oxisols (7, 10, 11, 12), ultisols (5, 6), alfisols (3, 4), inceptisols (8), entisols (1, 2),

Table 1. Some soil, climatic, and land use characteristics of the study sites

Locality and reference[a]	Symbol and number[b]		----Mean annual climatic data---- P (mm)	T (°C)	Soil order	Type of vegetation and/or crops
Senegal (a)	Psl	1	700	29	Entisol	Bush fallow, peanut, millet, sorghum
Senegal (a)	Ftl	2	700	29	Entisol	Grassfallow, peanut, millet
Senegal (b)	Fll	3	800	29	Alfisol	Tree savanna, peanut, millet
Ivory Coast (c)	Fl2	4	1360	26	Alfisol	Tree, bush and grass savanna
Ivory Coast (c)	Fr2	5	1360	26	Ultisol	Tree savanna, rice, corn, manioc
Togo (d)	Fr3	6	1040	27	Ultisol	Forest, corn-bush fallow
Guadeloupe (e)	Fr4	7	3000	25	Oxisol	Artificial meadow[c], market gardening
Martinique (e)	Fi6	8	1820	26	Inceptisol	Tree savanna, sugarcane, artificial meadow[c], market gardening
Martinique (e)	Ve6	9	1200	27	Vertisol	Tree savanna, artificial meadow[c], market gardening
Ste Lucia (e)	Fr7	10	2700	25	Oxisol	Grass fallow, corn, yam, market gardening
Brazil (f)	Fo8	11	1200	21	Oxisol	Forest, sugarcane
Brazil (g)	Fo9	12	1530	18	Oxisol	Prairie-rice, wheat, corn, soybean

[a]References: (a) Feller, 1994; (b) Feller and Milleville, 1977; (c) Fritsch et al., 1989; (d) Poss, 1991; (e) Albrecht et al., 1988; (f) Cerri et al., 1991; (g) Feller, 1994.

[b]The symbols refer to nomenclature used by Feller, 1994. Underlined site numbers correspond to smectitic soils.

[c]Planted with *Digitaria decumbens*.

Table 2. Some soil (0-20 cm) mineralogical and chemical characteristics of the study sites

Number[a]	Soil horizon (0-20 cm)						
	Mineralogy	F_2O_3t	0-20 μm	C	TRB[b]	CEC	$pH-H_2O$
	(0-2 μm fraction[a])	(g/100 g soil)			(cmol/kg soil)		
1	S-K-Q	1.2	13.6	0.58	22	5.7	5.9
2	K-I-Q	0.7	3.5	0.42	9	1.9	6.1
3	K-Q	1.0	18.7	0.75	10	nd[c]	6.4
4	K-Go	2.7	nd	1.16	18	nd	7.0
5	K-Hm	5.6	nd	1.58	16	nd	5.7
6	K-Q-(IS)	1.6	19.1	1.67	7	9.6	7.2
7	K-H-(Cri)	12.8	92.3	3.86	nd	15.5	4.8
8	K-H-Go-(IS)	14.0	63.1	4.41	135	24.0	6.4
9	S-(K)	nd	71.0	3.32	118	56.7	6.2
10	K-H-Go-(Cri)	nd	76.3	2.09	nd	14.8	5.3
11	K-Go-Hm-(Gi)	12.8	64.6	2.60	12	6.8	5.3
12	Gi-Hm-K	17.9	17.0	3.99	13	3.0	4.9

[a]Q = quartz, Cri = cristobalite, k = kaolinite, H = halloysite, S = smectite, I = illite, IS = interstratified clay, Go = goethite, Hm = hematite, Gi = gibbsite.

[b]TRB = Total reserve in bases according to Herbillon, 1989.

[c]not determined.

vertisols (9). The sandy soil, 1, and the clayey soil, 9, exhibit a clay fraction rich in smectite. The vertisol (9) is qualified as 'magneso-sodic' because exchangeable Mg and Na represent 30 to 40% and 5 to 10% of the total exchangeable cations, respectively. The selected LAC soils cover a wide range of texture, from sandy (2) to clayey (8, 10, 11, 12), with OC contents ranging from 0.4% (2) to 4.4% (8). The clayey LAC soils differ by their high (8) or very low (11, 12) Total Reserve in Bases (TRB) (Herbillon, 1989) in relation to the amount of primary weatherable minerals. For simplification, we will often distinguish four groups of samples. For LAC soils: (i) The coarse textured samples of kaolinitic soils from West Africa (sites 2 to 6); (ii) The clayey and TRB rich samples of kaolinitic/halloysitic soils from Antilles (sites 7, 8, 10); (iii) The clayey and TRB poor samples of kaolinitic/oxidic soils from Brazil (sites 11, 12). For HAC soils, the sandy smectitic (site 1) and the magneso-sodic vertisol (site 9) were selected.

B. Soil Organic Matter and Soil Aggregate Fractionation

Various methods adapted to aggregate size fractionation and soil organic matter distribution in particle size fractions were recently developed or improved and extensively used in the study.

1. Organic Matter Size Fractionation (OMSF)

The main OMSF method used in this study was described in Feller et al. (1991a). Briefly, it consists in shaking for 2 to 16 hours the 0 to 2 mm soil sample (40 g) in water (300 ml). The presence of a cationic resin (R) saturated with Na^+ improves the soil dispersion. Under these conditions, the pH of the soil suspension during fractionation was close to neutrality, and the OC solubilization was lower than 4%. This was followed by wet sievings at 200 and 50 μm to separate the coarse (200 to 2000 μm) and fine (50 to 200 μm) sand fractions. An ultrasonic treatment (US) of the 0 to 50 μm suspension (100J/ml) improved the clay dispersion. The coarse silt fraction (20 to 50 μm) was obtained by sieving. The fine silt (2 to 20 μm) was separated from clay (0 to 2 μm) by repeated sedimentations and the fine clay (0 to 0.2 μm) was obtained by centrifuging the clay (< 2 μm). C and N analysis were performed by dry combustion with a CHN Analyser (Carlo Erba, Mod. 1106).

The above method provided high dispersion of the soil constituents even with no application of ultrasonic treatment of the whole 0 to 2 mm soil sample. Balesdent et al. (1991) showed that an ultrasonic treatment of the whole soil may lead to an artificial transfer (about 50%) of OM associated with sands (plant debris) into the fine fractions (< 50 μm). The fractionation procedure was applied to 43 surface samples of the selected situations. The OM characteristics associated with the different size fractions may be succinctly described by the following (Feller et al., 1991 a, c):

(i) *fractions > 20 μm.* Predominance of 'plant debris' at different stages of decomposition are dominant with carbon to nitrogen (C/N) ratios ranging between 12 to 33 (mean value, mv = 20);

(ii) *fractions 2-20 μm.* 'Organo-silt complex' consisting of very humified plant and fungi debris associated with stable organomineral microaggregates which have not been destroyed during the fractionation. C/N ratios vary from 10 to 21 (mv = 15);

(iii) *fractions < 2 μm.* 'Organo-clay fractions' with predominance of amorphous OM acting as a cement for the clay matrix. Sometimes, under forest or savanna, presence of plant cell walls occurs in the coarse clay fraction but usually not in the fine clay. Very often, bacterial cells or colonies at different stages of decomposition can be observed in both fractions. C/N ratios vary from 7 to 12 (mv = 10). The microbial origin of amorphous OM in the clay fractions of these tropical samples agree with their very low xylose/mannose ratios (Feller et al., 1991 c).

Depending on the type of soil and soil management, the 20 to 2000 μm fraction, described as the 'plant debris fraction,' represented from 8 to 51% (mv = 26%) of the total OC content. In the 2 to 20 μm fraction the total OC content averaged from 11 to 40% (mv = 26%) and in the 0 to 2 μm fraction OC ranged from 20 to 70% (mv = 44%).

2. Aggregate Size Fractionation (AGSF)

The method applied to the selected samples was described in Albrecht et al. (1992a,b) and derived from methods of Yoder (1936), Williams et al. (1966) and Kemper and Rosenau (1986). It is based on kinetics of soil disaggregation in water under different shaking times. Soil samples were taken with a cylinder to preserve their structure, wetted to field capacity before treatment and shaken in water (35 g/250 ml) end over end (50 t/min) during variable times: 0, 0.5, 1, 2, 6, 12 and 18 hours. A supplementary 'time,' between time 0 and 0.5 hour was applied corresponding to the test of Henin et al. (1960) and consisting of 30 manual turnings (during about 1 min) and was named '30 t.' After shaking, the samples were sieved under water at 1000, 500, 200, 50 and 20 μm, then fractionated at 5 μm by sedimentation. The 'mean weight diameter, MWD' was graphically obtained from the median of the cumulative frequencies curve. Thus, 50% of the soil (by weight) will be in aggregate sizes under the value of 'MWD.'

C. Other Determinations

1. Henin et al. (1960) described an Instability Test (Is) given by the formula:

$$\text{Is} = \frac{(\text{A+LF}) \text{ max } \%}{1/3 \text{ Ag } \% - 0.9 \text{ SG } \%} \tag{1}$$

where '(A+LF) max %' represents the maximum amount of dispersed 0-20 μm fraction obtained after three treatments of the initial soil sample: without pretreatment (air) and with immersion in alcohol or in benzene. 'Ag %' refers to the > 200 μm aggregates (air, alcohol, benzene) obtained after shaking, i.e. 30 manual turnings and sieving under water of the 3 pre-treated samples. 'SG %' represents the content of coarse mineral sand (> 200 μm). The denominator of the formula (1/3 Ag % - 0.9 SG %) is an estimation of the 'mean percent stable aggregates.' It is often expressed by the decimal logarithm form of 10 x Is. This index is well related to the permeability estimated in the laboratory (Henin et al., 1960), and De Vleeschauwer et al. (1979) have shown that Is is also a very good index (among 14 others) of soil detachability in tropical soils.

2. Field rainfall simulation was applied on 1 m^2 surface at sites 8 and 9 with a mini-simulator (Asseline and Valentin, 1978). For the situations studied, the soil surface was prepared for a seed-bed using manual tillage at a 5 cm soil depth. Rainfall simulation was conducted on soils with high water contents to favor runoff (Le Bissonnais et al., 1990).

IV. Organic Matter, Structure and Cultivation in Kaolinitic and Smectitic Tropical Soils

Generally, clearing of the native vegetation followed by cultivation involves dramatic alterations in the morphology of the soil surface, together with a decrease in OC contents and aggregate stability.

A. Modifications of Soil Morphology in Soils under Cultivation

The type of structures encountered in different selected sites under native or long fallow vegetations and annual or sugarcane (*Saccharum officinarum* L.) crops are summarized in Table 3. Four types of situations can be distinguished:

(i) West African soils (sites 1 to 6), with coarse-textured surface horizons. The initial structure more or less massive/crumbly or polyhedral under native vegetation, appeared after 1 to 3 year-cultivation as being single-grain at the 5 to 10 cm soil depth accompanied by the formation of surface crust (Casenave and Valentin, 1989) and compaction of the horizon just below;

Table 3. Description of topsoil structure for the cultivated and non-cultivated study sites

Site	Non-cultivated		Cultivated	
number	Vegetation	Structure[a]	Vegetation	Structure[a]
1	Bush-fallow	Massive to cubic	Sorgho	Single grain and massive + crusts
2	Grass-fallow	Single grain to crumbly (fd)	Millet	Single grain and massive + crusts
3	Tree-savanna	Massive to crumbly (fd)	Peanut and millet	Single grain and massive + crusts
4	Tree-savanna	Massive to crumbly (fd)	nd[b]	
5	Forest	Crumbly (fd)	nd	
6	Forest	Crumbly to polyhedral (md)	Corn	Single grain and massive
7	Artificial meadow	Crumbly to polyhedral (wd)	Market gardening	Crumbly to polyhedral (wd)
8	Forest	Polyhedral (wd)	Food crops	Crumbly to polyhedral (wd)
9	Artificial meadow	Crumbly with prismatic over-structure (wd)	Market gardening	Cubic (large) and prismatic (large) (wd)
10	Grass-fallow	Crumbly to polyhedral (wd)	Food crops	Polyhedral (wd)
11	Forest	Polyhedral (wd)	Sugarcane	Pseudo-single grain and massive to lamelar
12	Natural meadow (campos)	Polyhedral (wd)	Corn, soybean	Pseudo-single grain and cubic to prismatic overstructure

[a]The development of structure is symbolized by : few (fd), moderately (md), or well (wd) developed.
[b]nd = not determined.

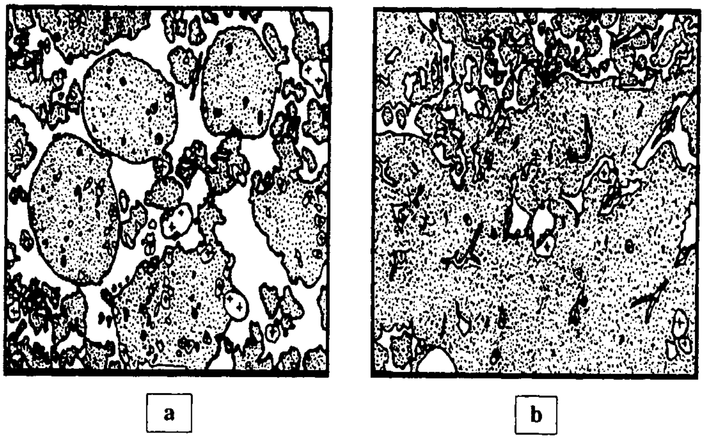

Figure 1. Optic microscopy (x 10) of the upper horizon (A1) of a clayey oxisol (Brazil, site 11) under (a) forest and after clearing and (b) 12 years of cultivation. Note the drastic diminution of macroporosity after cultivation. (Adapted from Cerri et al., 1991.)

(ii) In the clayey kaolinitic/halloysitic soils from volcanic origin (sites 7, 8, 10), a fragmental structure remained well developed with cultivation, more or less polyhedral, with some tendency to form larger overstructure;

(iii) In the highly weathered clayey oxisols of Brazil, the well-developed crumbly and polyhedral structure under native vegetation was rapidly changed (in 3 to 10 years), as in sandy soils, to a single grain-like structure over the 0-10 cm depth consisting of pseudo-sands. Below this depth the structure tended to be massive and/or prismatic or cubic;

(iv) In the magneso-sodic vertisol (site 9), the structure was dramatically modified with cultivation from crumbly in the 0-10 cm, under forest or meadows, to largely prismatic under annual crops.

These different morphological observations for kaolinitic soils are in agreement with those made in coarse-textured soils of Ivory Coast (De Blic, 1976; De Blic and Moreau, 1979), Brazil (Carvalho, 1990), in clayey oxisols of Congo (Mapangui, 1992) or Brazil (Cerri et al., 1991; Chauvel et al., 1991). These three last studies point out that the morphology and properties of the cultivated topsoil (Ap1 horizon) became similar to those of the initial savanna or forest subsoil (A/B horizons), and that after cultivation there was a dramatic reduction in meso- and macropores (> 5 μm) (Figure 1). If oxisols and ultisols are considered to have water stable aggregates (Greenland, 1979), as for alfisols, this structural aggregation did not survive the cultivation effects. In contrast, a well-developed structure seemed to be maintained in the younger kaolinitic/halloysitic volcanic soils of the Antilles (sites 7, 8, 10). The structure of the magneso-sodic vertisol was very sensitive to cultivation, while a stable structure

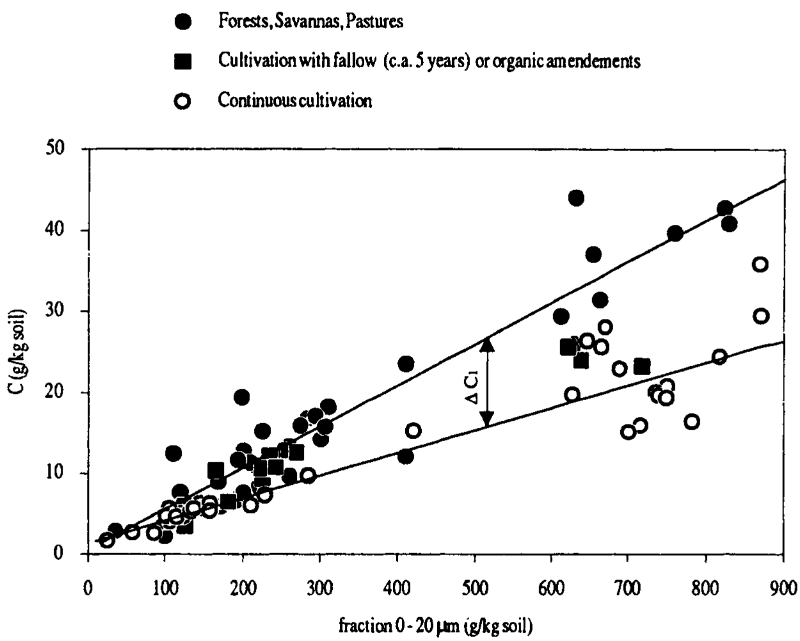

Figure 2. Variations in soil organic carbon (C) content of the 0-10 cm layer in relation with clay and fine silt fraction (0 to 20 μm) content of selected kaolinitic soils of West Africa, Antilles and Brazil. ΔC_l represents the mean differences in C between the non-cultivated (forest, savanna, pasture) and the continuous cultivated situations.

was generally described (Greenland, 1979) for cultivated calcic or calcareous vertisols.

B. Modifications in OM Contents and Structural Stability with Cultivation

The carbon contents of the 0 to 10 cm soil layers of 59 plots in the selected non-eroded sites are presented in Figure 2 (Feller, 1991d). The relative decrease in OC with cultivation (ΔC_l) was about 40% that of the initial OC whatever the soil texture. This result agrees with numerous studies already quoted in Introduction.

For the cultivated plots the linear regression between OC and 0 to 20 μm fraction % was:

$$C \text{ (g/kg soil)} = 0.294 \text{ (0-20 } \mu\text{m \%)} + 0.31 \qquad (2)$$
$$(n = 25,\ r = 0.95,\ p < 0.01)$$

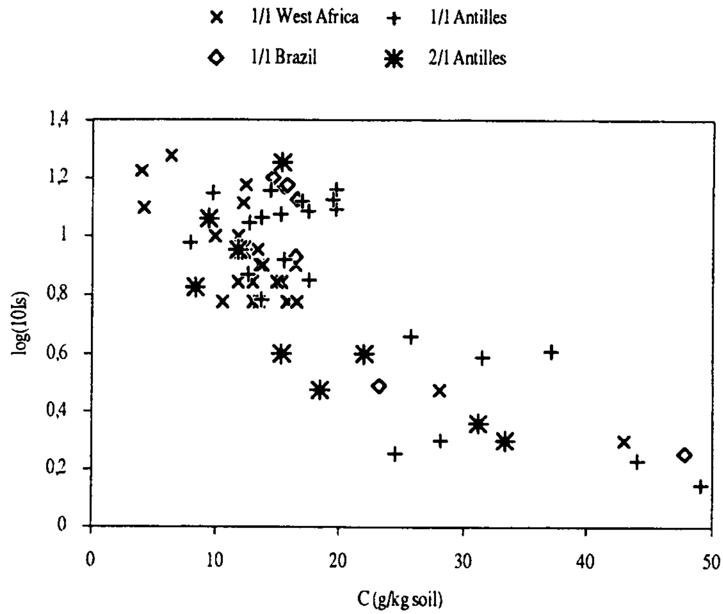

Figure 3. Relationships between the Henin's structural instability index (Is) and the organic carbon content (C) of selected kaolinitic (1/1) and smectitic (2/1) soils of West Africa, Antilles and Brazil. Surfaces horizons 5 to 15 cm. Is is expressed in form of $\log_{10}$ (10xIs). For the Is formula see text.

It was very close to that of Lepsch et al. (1982) for cultivated soils in Brazil:

$$C(g/kg\ soil) = 0.325\ (0\text{-}20\ \mu m\ \%) + 0.77 \quad (n = 87,\ r = 0.81,\ p < 0.01) \tag{3}$$

Henin's test (Is) was applied to 60 soil samples from the reported sites. Figure 3 illustrates the high correlation (r = - 0.79) between log (10 x Is) and C % contents of the surface horizons, while the correlation between log (10 x Is) and 0-20 μm % was non-significant (r = - 0.08). Significant correlations between Is and OC contents were also given by Combeau (1960), Combeau et al. (1961), Thomann (1963) and Martin (1963) for African oxisols. With the water stable aggregates (WSA) tests, Goldberg et al. (1988) showed significant correlations between WSA and OC for diverse Californian soils. Similar conclusions were provided by Alegre and Cassel (1986) for a fine loamy ultisol of Peruvian Amazon, by Dutartre et al. (1993) for sandy alfisols of West Africa, and by Arias and De Battista (1984) for Uruguyan vertisols.

The relationships between OM and aggregation for each type of soil may be summarized by the detailed analysis of the distributions of both OM and aggregates within the bulk soil.

C. Modifications in OM Distributions in Particle Size Fractions with Cultivation

As seen in Section III.B.1., size-fractionation allowed the separation, in a first approximation, of three types of organic compartments: (i) the plant debris fraction (> 20 μm); (ii) the organo-silt complex (2-20 μm) composed of humified plant and fungi debris and of very stable microaggregates; and (iii) the organo-clay fraction dominated by amorphous OM of partly microbial origin.

The OMSF procedure using Na-resin was applied to samples from the 0 to 10 cm depth on cultivated and non-cultivated plots corresponding to situations 1 to 11. The detailed results on the carbon contained (g C/kg soil) in the three size fractions of each sample were given in Feller et al. (1991d). Here, the differences, ΔC_2 (g C/kg soil), of OC contained in each fraction that appeared with changes in soil management are reported (Figure 4). Different types of soil management were studied (comparisons of Figure 4, a to d) for soils with different textures (Figure 4, a1 to a3, b1 to b3 etc...) or different mineralogies (Figure 4, c3 and c3 bis). The examples show: (i) the decrease in OC contents following clearing and continuous cultivation during 10 years (Figure 4a) or, (ii) the increase in OC contents following: spontaneous fallowing (6 to 10 years) (Figure 4b), 10 years of artificial meadow (Figure 4c) and 4 years of composted straw inputs (Figure 4d).

After continuous cultivation, the decrease in soil OC contents (negative ΔC_2) was mainly due to the decrease of the plant debris fraction in sandy soils (Figure 4a1) and of the OC-clay fraction in clayey soils (Figure 4a3). The 0 to 20 μm fraction and the sandy clayey soil (Figure 4a2) gave intermediate variations. After fallow or meadow, the increase in soil OC contents (positive ΔC_2) was mainly due to the amount of the plant debris fraction in sandy soils (Figure 4b1 and 5c1) and to both plant debris and organo-clay fractions in clayey soil (Figure 4b3 and 4c3). Increases in the 2 to 20 μm fraction were limited. The vertisol (Figure 4c3 bis) showed similar variations to ferrallitic soils (Figure 4c3). Following compost addition, the increase in soil OC contents in sandy soils (Figure 4d1) was largely due to the increase of the plant debris fraction.

All these results suggest that over a medium to a long term scale (> 5 years), the effects of soil management on soil OC variations will differ quantitatively and qualitatively in relation to soil texture. In coarse-textured soils a large part of the OC variations is mainly due to the variations in the plant debris fractions. Similar results were observed by Djegui et al. (1992) and Bacye (1993) for sandy to sandy clayey LAC soils of Benin and Burkina-Faso, respectively. This apparent high turnover rate of plant debris is confirmed for tropical situations, by the study of OC dynamics using the ^{13}C approach (Cerri et al., 1985;

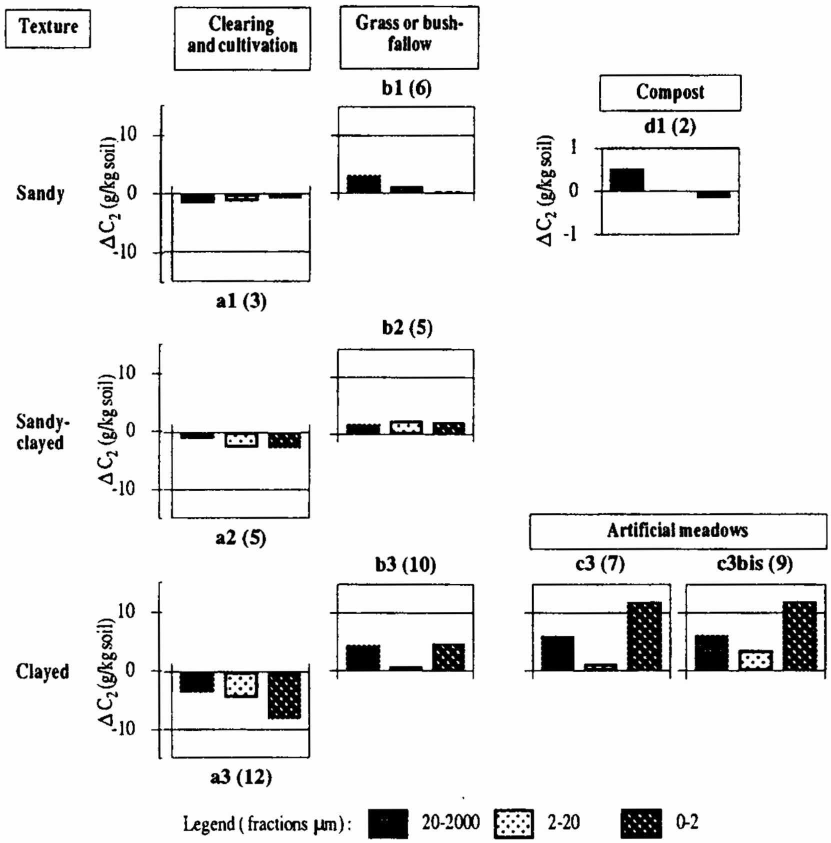

Figure 4. Effect of texture and different types of soil management on the variation (ΔC_2) of organic carbon contained in the 20 to 2000, 2 to 20 and 0 to 2 μm fractions (gC/kg soil) of the 0-10 cm horizons. The corresponding site numbers are indicated in parentheses and refer to Tables 1 and 2. $\Delta C_2 < 0$ = decrease of carbon, $\Delta C_2 > 0$ = increase of carbon. Compost refers to plots fertilized with millet straw compost during 4 years (about 10 t DM/ha/year).

Balesdent et al., 1987 and 1988), for coarse-textured LAC soils (Martin et al., 1990; Trouve et al., 1991; Desjardins et al., 1994) as well as for the clayey oxisol of site 11 (Cerri et al., 1985; Feller et al., 1991b; Bonde et al., 1992). In contrast, in fine-textured soils and especially in clayey soils, the high absolute OC variations are mainly due to the 0 to 2 μm fraction even if fallow or meadow effects explain the decrease or increase in plant debris fractions due to differences in root growth. This implies that a relatively large portion of OC associated with clay fractions is apparently labile. From the results of Martin et al. (1990), Feller et al. (1991b) and Desjardins et al. (1994) obtained using the

^{13}C approach, it was calculated that about 20 to 40% of the OC associated with the clay fraction were renewed during a period of 9 to 16 years.

Combining the data from different sites, the values of OC contained in each fraction (g C/kg soil) are summarized in Figure 5 for non-cultivated (NCULT) and cultivated (CULT) situations, in relation to soil texture (0-2 μm fraction weight). In terms of statistical relationships the following points can be stressed:

(i) In both CULT and NCULT situations there is a positive effect of texture on OC contained in the organo-clay fraction, but;

(ii) The CULT and NCULT situations differ for the organo-silt complex and plant debris fraction (i.e. no significant correlation for CULT, and tendency to significant correlation for NCULT). This might be interpreted in terms of a protective effect of aggregation on the plant debris fraction: significant effect for soils with high structural stability (NCULT situations), no effect for soils with low structural stability (CULT situations).

D. Modifications in Water Stable Aggregate Distributions with OM Contents and Cultivation

1. Approaches to Characterize Water Stable Aggregates

There does not exist a standardized and international accepted approach to the 'Water Stable Aggregate' (WSA) concept, both for the energy applied in the disaggregation technique as well as for the choice of normalized particle size classes. In regard to the energy applied, the shaking duration time may vary from minutes to hours according to the objectives of the studies.

Three main approaches are used to characterize WSA, based on specific aggregate size or whole soil analysis. The most currently used methods for the first approach are based on single- or multiple-sieve techniques, but the considered aggregate sizes may vary considerably. As examples for tropical situations, the smallest diameter is 100 μm for Oliveira et al. (1983) and Alegre and Cassel (1986), 250 μm for Arias and De Battista (1984), Goldberg et al. (1988) and 500 μm for Ike (1986) and Ekwue (1990). From the works of Edwards and Bremner (1967) the size of c.a. 250 μm is often considered as a boundary between macro- ($> 250\mu$m) and microaggregates (< 250 μm) and numerous recent studies of aggregate stability accord a great importance to the WSA larger than 200 or 250 μm (Tisdall and Oades, 1982; Utomo and Dexter, 1982; Arias and De Battista, 1984; Elliott, 1986; Goldberg et al., 1988; Pojasok and Kay, 1990; Miller and Jastrow, 1990; Haynes et al., 1991; Angers, 1992; Carter, 1992; Beare and Bruce, 1993). However, with such methods, information is generally lacking about the process of disaggregation: slaking or dispersion. The second approach to characterize WSA is used in some cases where soils are rich in swelling clays and/or exchangeable sodium and is based on the measurement of the 'dispersed' fractions (0 to 2 or 0 to 20 μm) (Oliveira et al., 1983; Goldberg et al., 1988; Dalal, 1989). Surprisingly, the use of the

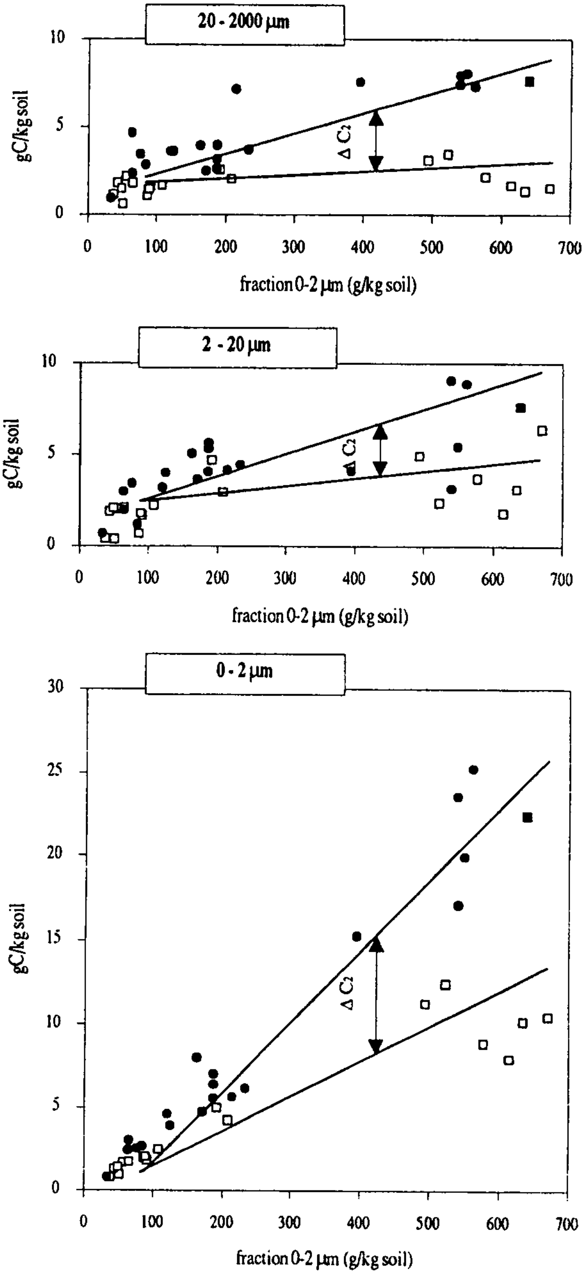

Figure 5. Relationships between the organic carbon (C) contained in the 20 to 2000, 2 to 20 and 0 to 2 μm fractions (gC/kg soil) from cultivated (□) or non-cultivated (●) situations. Horizons 0-10 cm of selected kaolinitic and smectitic soils of West Africa, Antilles and Brazil. ΔC_2 represents the mean differences in C between the non cultivated and the cultivated situations.

third approach to characterize WSA, which consists in whole aggregate size analysis from the macroaggregates to the dispersed 0 to 2 μm fraction on the same sample, and takes into account the energy input level, is relatively scarce. Oades and Waters (1991) published some examples of such a complete approach for WSA distribution, that allowed these authors to discuss the concept of 'aggregate hierarchy' according to soil type. We will present In the next section data (Albrecht et al., 1992b and unpublished) obtained with such an approach for cultivated and non-cultivated soils of West Africa, Antilles and Brazil.

2. Water Stability of Macro- and Microaggregates of Selected Kaolinitic and Smectitic Tropical Soils

The methodological aspects of this section are described in section III.B.2. Simplified results are presented in Figure 6 for three main aggregate classes: the macroaggregates larger than 200 μm, the secondary microaggregates 5 to 200 μm, and the primary microaggregates 0 to 5 μm. For each situation a non-cultivated (NCULT) soil (forest, savanna, grass or tree-fallow, meadow) rich in OC is compared with a cultivated (CULT) and poor in OC soil.

The kinetics of the disaggregation of macroaggregates differ according to the soil type and the soil OC content. For the sandy clayey West Africa soil and the vertisol, macroaggregates are destroyed in about 0.5 to 1.0 hour, while 6 hours at least are necessary for the clayey LAC soils of Antilles and Brazil. The effect of OC contents varies also with the soil type: it had a relatively low effect on soils with low macroaggregate stability (West Africa LAC soils and Vertisol), but a more important effect for the other soil types. The stability of secondary microaggregates (5 to 200 μm) differs with soil type also. For the sandy clayey soil of Africa, few microaggregates remain after 2 hours (values close to that of the mechanical analysis), whatever the OC content. For the vertisol, the stability of microaggregates depends on the OC content of the sample, whereas the clayey LAC soils of Antilles and Brazil display high microaggregates stability, whatever the OC content.

The examination of the curves for the primary microaggregates (0-5 μm) provide precise information on the relative importance of the slaking effect (disruption of macroaggregates into secondary microaggregates) and the dispersion effect (disruption with dispersion of finer colloidal materials) during the disaggregation process. For example, the cultivated vertisol is characterized by a large and immediate (t_0 or 30 turnings) dispersion effect compared with the other cultivated soils, but this effect is strongly reduced with a high OC content. In the other soils, significant dispersion effects appear with larger shaking durations.

Finally, to characterize the water stability of aggregates, it seems important to take into consideration: (i) the different classes of macro- (> 200 μm), secondary micro- (5 to 200 μm), and primary microaggregates (0 to 5 μm), and (ii) the level of energy input utilized in a kinetic approach. The latter may be

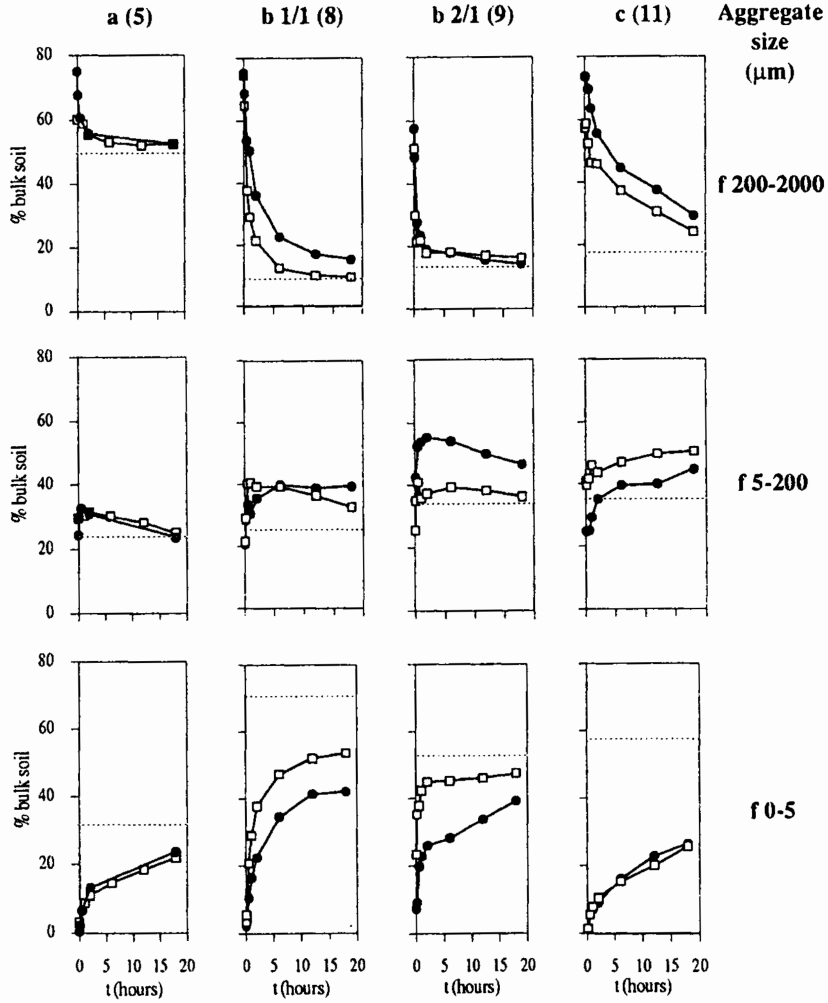

Figure 6. Variations with the shaking time (t) of the weight of macro- (> 200 μm) and micro- (5-200 and 0-5 μm) aggregates of the 0-10 cm layer of selected kaolinitic (1/1) and smectitic (2/1) soils of West Africa (a, site 5), Antilles (b, sites 8 and 9) and Brazil (c, site 11). Black signs (●) are rich OM samples: a = savanna, b = pasture, c = forest. White signs (□) are poor OM samples: a = 10-year food crops, b = 10-year market gardening, c = 12-year sugarcane. The dotted line (...) represents the weight of the corresponding size fraction obtained by mechanical analysis (H_2O_2 treatment and dispersion).

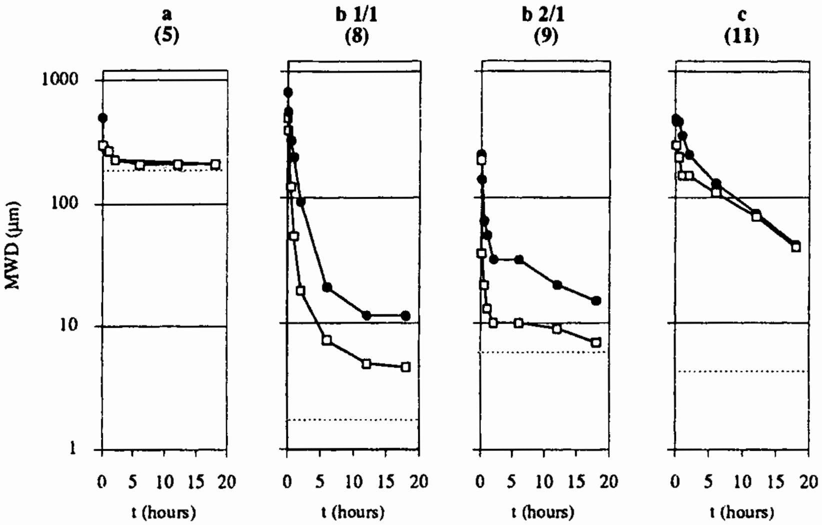

Figure 7. Variations with the shaking time (t) of the mean weight diameter MWD (μm) of selected samples from kaolinitic (1/1) and smectitic (2/1) soils of West Africa (a), Antilles (b) and Brazil (c). The corresponding site's number refers to Tables 1 and 2. Horizons 0-10 cm. Black signs (●) are rich OM samples: a = savanna, b = pasture, c = forest. White signs (□) are poor OM samples: a = 10-year food crops, b = 10-year market gardening, c = 12-year sugarcane. The dotted line (...) represents the MWD obtained by mechanical analysis after H_2O_2 treatment and dispersion (MWDm).

very informative in characterization of water stable aggregates. For example, an integrated representation of the WSA distribution may be obtained from the kinetic curve of the mean weight diameter (MWD) of the sample (Figure 7). The differences with soil type and OC level are also clearly shown with such a representation. If we consider a given shaking duration (i.e. 0.5 hour) there exists, for the LAC samples, a highly significant positive correlation ($p < 0.01$) between $\Delta MWD_{0.5}$ and OC content. ΔMWD is the mean weight diameter of the 'aggregated material' and is calculated by the difference between $MWD_{0.5}$ and MWD_m, if MWD_m represents MWD obtained by mechanical analysis (after H_2O_2 treatment and dispersion). Significant correlations ($p < 0.05$ or < 0.01) between ΔMWD and OC were also reported by Alegre and Cassel (1986) for an ultisol of Peruvian Amazon after clearing and a subsequent 2 year-cultivation, even with relatively low variations (20%) of OC contents; and by Arias and De Battista (1984) for vertisol of Argentina; and by Haynes and Swift (1990), Angers (1992), Carter (1992) for non-tropical soils.

3. 'Aggregate Hierarchy' in the Studied Tropical LAC Soils

Oades and Waters (1991) have proposed an evaluation of 'hierarchy' for aggregate stability based on the particle size distributions of aggregates destroyed between two treatments of different energy. According to these authors, the concept of 'aggregate hierarchy' is based on the 'principle that disaggregation will occur due to planes of weakness between stable aggregates'.... 'Therefore, it should be possible to determine whether an hierarchical order of aggregates exists or not by systematic studies of disaggregation as disruptive energy is increased. If aggregates breakdown in a stepwise fashion then hierarchy exists. If aggregates breakdown to release silt and clay size materials directly then there is not an hierarchical order '....' The concept may not apply to clods formed from strongly sodic clays in which planes of weakness are rare.' The Oades and Water's examples are reported in Figure 8d for selected oxisol, mollisol and alfisol. Two types of curve can be described, one with a 'maximum' (mollisol and alfisol), the other with a plateau (oxisol). The first type indicates that as the disruptive energy increases during the destruction of the macroaggregates a dominant class of stable microaggregates appears. Their mean diameter corresponds to the maximum diameter. For lower diameters, the regular decrease of the curve denotes the presence of different classes of smaller stable microaggregates but without significant release of clay particles or clay-size microaggregates. This hierarchical order of stable aggregates with limited dispersion processes corresponds to the concept of 'Aggregate Hierarchy.' In contrast, the presence of a plateau illustrates the absence of an hierarchical order for the stable microaggregates and the existence of important dispersion processes together with the apparition of clay particles or clay-size microaggregates.

Such an approach was applied to our situations for non-cultivated or cultivated situations under approximately the same experimental conditions as those of Oades and Waters (1991) in using data of the t_0 and t_{16} hour treatments (Figure 8a to 8c), after 16-hour shaking treatments. A tendency to an aggregate hierarchy appeared for the LAC soils (sites 5, 8, 11), cultivated or non-cultivated, but not at all for the vertisol (9). The hierarchy for LAC soils is not so clear as that in the mollisol and alfisol studied by Oades and Waters (1991). This contrasted behavior is due to the existence of an high dispersion effect at 16 hours for all the LAC soils as shown in Figure 6: the % weight differences for the 0-5 μm fraction t_0 and t_{16} hours vary from between 20 to 50 %. However an OC effect corresponding to the maximum of the curves (Figure 8) is visible on the aggregate size: for non-cultivated LAC soils (rich in OC) the stable aggregate diameter is close or larger than 100 μm, while for cultivated LAC soils (poor in OC) it is comprised between 20 to 50 μm. Using a 'fractal' approach, Bartoli et al. (1992) have demonstrated that the size of the elementary structural pattern of oxisols decreases as a function of OM content. This result is in aggreement with the hypothesis that OM leads to the development of an

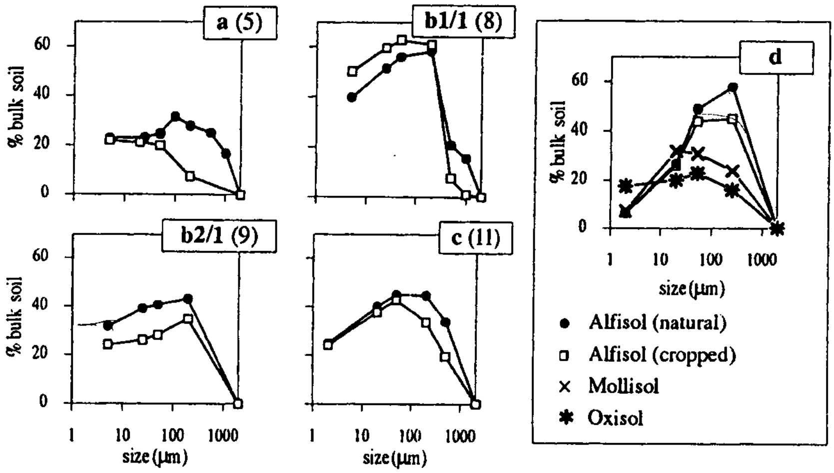

Figure 8. Application of the 'aggregate hierarchy' approach (Oades and Waters, 1991) to selected kaolinitic and smectitic soils of West Africa (a, site 5), Antilles (b, sites 8 and 9) and Brazil (c, site 11). Figures a, b and c may be compared with the figure d adapted from the Oades and Waters' results obtained with uncropped and cropped alfisol (South Australia), mollisol (Canada) and oxisol (Queensland, Australia). The alfisol and mollisol curves are characteristics of samples showing an "aggregate hierarchy"; it is not the case for the oxisol curve. The y scale (8d) represents the weight difference (%) between t_0 (with 0 is the shaking time in hours) and t_{18} (or t_{16} for the figure d) calculated from the corresponding cumulative frequencies curves. Black signs (●) are rich OM samples: a = savanna, b = pasture, c = forest. White signs (□) are poor OM samples: a = 10-year food crops, b = 10-year market gardening, c = 12-year sugarcane.

'aggregate hierarchy.' More studies are yet necessary to confirm the validity of such a concept for tropical soils.

4. Conclusions to the Effects of Cultivation on the Distributions of OM and Water Stable Aggregates

The different observations and results presented here for the tropical situations may be summarized as follows:

(i) With changes in soil management, the resulting changes in soil OC distribution are closely related to soil texture whatever the soil mineralogy: for coarse-textured soils, variations concern mainly the plant debris fraction, for fine-textured soils variations concerned both the plant debris and organo-clay fractions;

(ii) In terms of water stable aggregate distribution the consequences are more complex and may also take into consideration the characteristics of the mineralogical and ionic environment. For the LAC, coarse-textured West Africa kaolinitic soils (Figure 6a), the macroaggregates are unstable. The OC effect (plant debris effect) is only significant at a low energy input (up to 30 turnings) and acts on the slaking process (no differences in the dispersed 0 to 5 μm fraction). For the kaolinitic / halloysitic clayey soils of Antilles (Figure 6b 1/1), the macroaggregates are relatively stable. The OC effect acts first (plant debris OC effect) on the slaking process at a low energy input, then on the dispersion process (organo-clay OC effect) at high energy inputs. For the Brazilian oxisols the macroaggregates appear very stable. The OC effect (both plant debris and clay OC effects) acts only on slaking, the stabilization of clay fraction (0 to 5 μm) in secondary microaggregates (5 to 200 μm) being more controlled by oxides than by humified and amorphous OM. For all types of the studied LAC soils, OC content affects the 'aggregate hierarchy.' In regard to the magneso-sodic vertisol of Antilles (Figure 8b 2/1), the macroaggregates are very unstable. The OC effect acts mainly by a dramatic limitation of the dispersion process (clay OC effect).

E. OM Distribution in Water Stable Aggregates in Relation to Soil Type and Cultivation

WSA distributions vary according to the applied disruptive energy, the soil type and the cropping system (or soil OC content). Therefore the OC-aggregate distribution (OC in % of total soil OC) will depend on these three factors. Figure 9 gives examples for a magneso-sodic vertisol (site 9) and a clayey LAC soil (site 8). For each soil we compared plots corresponding to market-gardening (m) or intensified pastures (p) and soil surface samples submitted to low (AGSF at time 0, t_0) or high (AGSF at time 6 hours, t_6) disruptive energy, the maximum disaggregation effect being obtained with the organic matter size fractionation (OMSF).

In the case of the vertisol, at time 0 with market-gardening, the OC-aggregate distribution is already close to that obtained by OMSF, with the highest OC-aggregate percentage (55%) found in the primary microaggregates (> 5 μm). This result is completely different to that of the clayey LAC soil in which the highest OC-aggregate percentage (75%) is found among the macroaggregates (> 200 μm). Under pastures (high OC content sample) the OC-aggregate distributions at time 0 was rather similar for the two soils with a dominant location of OC in the macroaggregates (> 200 μm). Even after a 6-hour shaking the OC-aggregate distribution in the vertisol under pasture remains very different from the distribution obtained by OMSF, the highest OC-aggregate percentage (47%) being found in the microaggregates (5 to 200 μm).

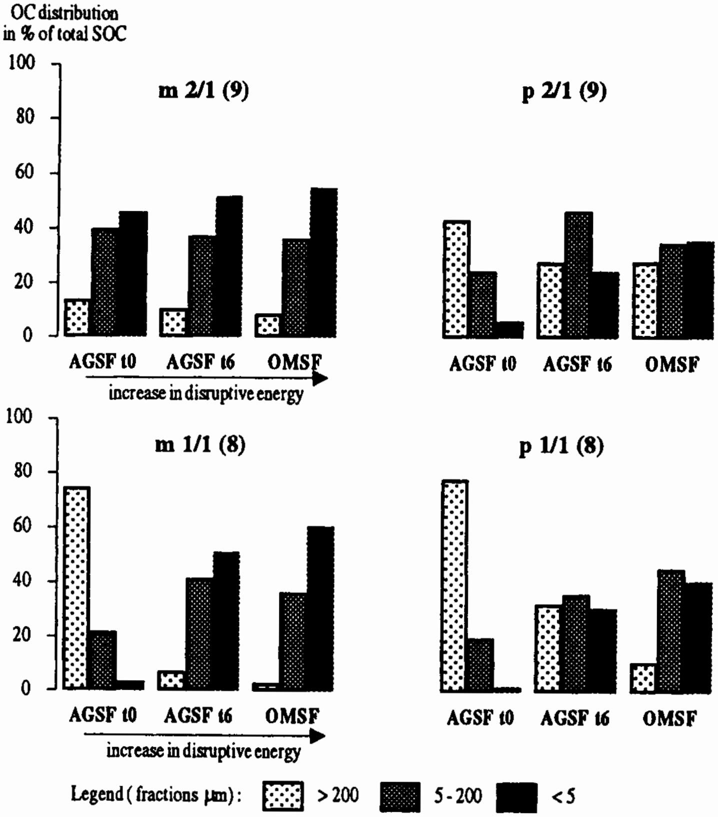

Figure 9. Organic carbon (C) distribution in the different water stable aggregates obtained after 0 (AGSF, t_0) and 6 hours (AGSF, t_6) shaking of a vertisol (site 9) and a clayey LAC soil (site 8). Plots corresponding to market gardening (m) or pasture (p). Comparison with the OC distribution obtained by organic matter size fractionation (OMSF). Results expressed in % of the total soil C.

V. Soil Biota and Organic Constituents and the Stabilization of Structure

Modifications in structural stability are apparently strongly dependent on OM contents. However, in several instances, changes in OM due to soil management are very often accompanied by changes in soil biological activity such as root development, microbial (algual, bacterial and fungal) or faunal activities. For example, in a vertisol (site 9) and a kaolinitic/halloysitic soil (site 7), the positive effects of meadow on aggregate stability (Is) may be due not only to an increase in total OM or in specific organic constituents but also to an increase in root biomass, bacterial activity (as reflected by C and N mineralization) and/or macrofauna activity such as earthworms (Table 4). The following illustrates some effects of soil biota and specific organic constituents on the structural stability of tropical soils.

A. Role of Soil Biota in the Stabilization of Soil Structure

1. Roots and Microbial Effects

Australian soil scientists have developed models of different organic and biological binding agents as well as basic mechanisms involved in the stability of soil structure (Tisdall and Oades, 1980 and 1982; Oades, 1984 and 1993; Oades and Waters, 1991). They also examined the implications as far as soil management is concerned. Two levels of soil aggregation are generally considered:

(i) The soil macroaggregates ($> 250\ \mu$m) which are mainly stabilized by a 'packing' effect due to the network of living roots and hyphae, particularly the vesicular-arbuscular mycorhizal (VAM) hyphae. These agents, classified as temporary binding agents, are more or less associated with transient polysaccharides. This approach emphasizes the role of soil management, i.e. crop rotation and agricultural practices, on soil structure;

(ii) The microaggregates ($< 250\ \mu$m) are mainly stabilized by more persistent organic or organometallic binding agents including small plant and fungal debris, aromatic humic materials and amorphous OM polysaccharides, originated from root, fungi and bacteria. The microaggregate stability could be an intrinsic characteristic of the soil, not greatly dependent on soil management.

This *in situ*-approach was confirmed by Dorioz et al. (1993) with *in vitro* laboratory experiments conducted to determine the respective effects of fungi, bacteria and roots on the arrangement of kaolinitic and smectitic clay particles. Dorioz et al. (1993) distinguished the following effects:

(i) 'Packing' effects due to the network of fungal hyphae and fine roots and their consequences on the 50 to 200 μm aggregate genesis;

(ii) 'Mechanical' effects which contribute to modified particle arrangements either by root and hyphae penetration and compaction associated with dehydration and reorientation of clay particles. It is stressed that bacterial and fungal cells and roots are located in the 5 to 20 μm and 50 to 200 μm sites, respectively;

(iii) 'Polysaccharidic' effects with the formation of a clay-polysaccharide complex (CL-PS) on a 1 μm scale for bacteria and 50 μm for roots.

Important changes in particle arrangement of kaolinite were observed while with montmorillonite an adhesion of cells and/or polysaccharides to the quasi-crystals was observed. The effect of polysaccharides from different origin (vegetal, fungal, microbial) was also reported in details by Chenu (1993).

Table 4. Comparisons of some soil properties (0-10 cm) of a vertisol (site 9) and a clayey LAC soil (site 7) under pasture (p) or market-gardening (m)

				Biomass		Mineralization tests	
Site number	Vegetation	Henin's test	SOC[a] (g C kg^{-1} soil)	Root (g C kg^{-1} soil)	Macrofauna (g m^{-2})	C (mg kg^{-1})	N (mg kg^{-1})
9	m	0.70	11.6	0.12	3.1	650	21
	p	0.27	32.9	10.1	366.4	1760	179
7	m	1.24	22.7	nd[b]	3.3	650	96
	p	0.14	40.1	nd	52.2	1430	255

[a]Soil organic carbon; [b]not determined.

These *in situ* or *in vitro* observations are in good agreement with our own descriptions of size OM fractions, their locations in soils or aggregates of tropical situations and the relation between OM and WSA distributions (this chapter, and Chotte et al., 1993). In contrast, the idea that macroaggregation would be mainly dependent on soil management and microaggregation on intrinsic soil characteristics does not fit well with results reported in section IV.C for the vertisol and oxisol (Figure 6b 2/1 and 6c). For these two situations the stability of secondary microaggregates is also largely dependent on OC content and soil management.

2. Faunal Effects

Earthworms and termites represent by their biomass and their activities the most important soil macrofauna communities in relation to soil behavior and properties as well as SOM dynamics and physical properties (Garnier-Sillam, 1987; Lavelle, 1987; Lal, 1988; Lavelle et al., 1992; Brussaard et al., 1993). With land management practices, soil macrofauna diversity and/or activity are assumed to change as mentioned above (Table 4) and reported recently by Lavelle and Pashanasi (1989) and Fragoso et al. (1992) for numerous tropical situations.

For both earthworms and termites, it is necessary to distinguish three main functional groups depending on feeding (surface litter or SOM including roots) and location of animals in the profile (Lavelle et al., 1992). *Epigeics* live and feed in the litter. *Endogeics* live in the soil and feed on SOM and mainly dead roots (living roots seem to be a poor resource). *Anecics* live in the soil (or in epigeic nests for some termites) but feed in the litter. Endogeics and anecics exert the most important influence on SOM dynamics and physical properties. Anecics can enrich the upper soil layer in OC by mixing soil with litter debris, while endogeics do not. Therefore, this last group, especially earthworms, can be used in controlled experiments to show specific faunal effects on aggregation with a limited interference with exogenic-soil OM inputs.

3. Earthworms and Soil Structure

In the field, earthworm casts are generally richer in OC and have a higher aggregate stability than the non-ingested soil due either to the incorporation of litter OM or to a selection of finer soil particles (Roose, 1976 and Fritsch, 1982 results quoted in Feller et al., 1993; Mulongoy and Bodoret, 1989). As structural stability is strongly correlated to OC, it is difficult to attribute a specific effect of earthworms on *in situ* structural stability. Hence, controlled experiments were generally conducted with endogeic earthworms which dominate in the humid tropics. Blanchart (1990) estimated that the weight of new endogeic earthworm aggregates represent about 50 to 60% of an alfisol surface horizon under savanna in Ivory Coast.

The specific effect of an endogeic pantropical earthworm (*Pontoscolex corethrurus*) on the structure of a vertisol was clearly demonstrated from electron microscopic strudies by Barois et al. (1993). They showed that the soil structure was first completely destroyed during the transit in the anterior gut by the swelling and dispersion of the clay particles in a semi-liquid medium rich in free polysaccharides. At the end part of the gut and in casts, the soil is restructured with the formation of new aggregates due to interactions between clay particles, polysaccharides and microbial colonies. Because the material was dispersed during the gut transit, a certain instability of the fresh casts compared to that of the non-ingested soil was observed. In contrast, after drying and ageing, the aggregate stability of the casts was higher in relation to their OC contents and colonization by fungal hyphae (Shipitalo and Protz, 1988; Marinissen and Dexter, 1990). This positive and specific effect of endogeic earthworm on aggregation and stability was also demonstrated for poorly structured alfisol in Ivory Coast by Blanchart (1992) and Blanchart et al. (1993). After 28 months, the water stability of aggregates (> 2 mm) increased in the different treatments according to the following order:

Milsonia anomala > *Eudrilidae* > Control (Natural Savanna) > No Earthworms.

This increase in water aggregate stability may be accompanied by an increase in bulk density and decrease in mean pore sizes (De Vleeschauwer and Lal, 1981; Blanchart et al. 1993), but Martin and Marinissen (1993) quoted other contradictory results in the literature (Joschko et al., 1989; Elliott et al., 1990). Brussaard et al. (1993) also observed in a Nigerian alfisol an important decrease in voids > 30 μm which was attributed to low earthworm activity especially when mulch practices were absent.

4. Termites and Soil Structure

The study of morphological characteristics of the edaphic material in termite mounds is well documented (Sleeman and Brewer, 1972 ; Kooyman and Onck, 1987), but there are few studies on termite soil aggregates. Garnier-Sillam et al. (1985) described the microaggregates from the feces of four species of termites, and Eschenbrenner (1986) emphasized the similarity of aggregates between termite-inhabited soils and mounds. According to Lavelle et al. (1992) much progress remains to be made in this area.

The effects of termites on structure may be variable. In a Congo ultisol, Garnier-Sillam et al. (1988) reported a positive effect of *Thoracotermes macrothorax* on aggregate stability in relation to an enrichment in OM. With *Macrotermes mülleri,* mound constructions were poor in OM and aggregate stability was low in comparison to those of the soil A horizons. According to Roose (1976) and Janeau and Valentin (1987) termites may also cause soil crusting and therefore increase runoff.

B. Role of Specific Soil Organic Constituents in the Stabilization of Soil Structure

This subject can be studied on various scales of soil organisation: (i) bulk soil sample, and (ii) aggregates or size fractions. Experimental models were also used to better understand involved mechanisms, especially organo-clay interactions. As few data are available on tropical soils, examples of both tropical and temperate situations will be mentioned.

1. Studies on Bulk Soil Samples

Diverse families of soil organic compounds were studied in respect to their aggregative properties. Using classical chemical studies of SOM, Combeau (1960), Martin (1963) and Thomann (1963) found that the structural stability of tropical LAC soils was more related to the humin fraction (total carbon minus acid and alkali extractable fractions) than to fulvic or humic acids. This result is in agreement with the data of Dutartre et al. (1993) for sandy tropical alfisols who showed that stable aggregation may be related to high contents of humin, uronic acids, osamines and polyphenols. In contrast, for non-tropical soils, Chaney and Swift (1984) and Piccolo and Mbagwu (1990) attributed a positive effect to humic and fulvic acids in the stabilization of structure.

Giovanni and Sequi (1976 a,b) and Wierzchos et al. (1992), used organic solvents (acetylacetone/benzene) to isolate organic constituents involved in aggregation. They emphasized the role of the associated mineral cations, especially iron and aluminium. Hamblin and Greenland (1977) showed that organic materials removed by acetylacetone or pyrophosphate had a more important effect on aggregate stability than polysaccharides. On the other hand, other organic constituents such as phenolic substances (Griffiths and Burns, 1972) or SOM 'alphatic fraction' extracted by super-critical hexane and characterized by hydrophobic properties (Capriel et al., 1990) were also considered efficient in the stabilization of structure. Hayes (1986) also estimated that the most efficient molecules in maintaining soil stability would have linear or linear helix conformations in solution, for such conformations would span the longest distances.

However, most of the studies on soil stucture stability were concerned with polysaccharides (PS), and it was shown that these compounds act as glues inside soil aggregates (review in Cheshire, 1979 and Tisdall and Oades, 1982). Nevertheless, their relative importance in comparison with others compounds (see above) may be questioned (Hamblin and Greenland, 1977). PS mainly act as transient compounds on a short-term scale (Tisdall and Oades, 1982), the correlations between total carbohydrate contents and aggregate stability were not necessarily significant (Baldolk et al., 1987). Based on the sugar composition of the PS fraction, Cheshire et al. (1983 and 1984) concluded that PS of microbial origin were more efficient than plant-derived PS. This agrees with the results of Sparling and Cheshire (1985) who observed that the polysaccharidic effect on aggregate stability was less important in rhizosphere than it was in the non-rhizospheric soil because a large part of PS might be in the form of plant remains and debris. However Benzing-Purdie and Nikuforuk (1989) stressed the importance of the PS of plant root origin for soil aggregation. For a New Zealand cambisol and inceptisol, Haynes and Swift (1990) and Haynes et al. (1991) found that aggregate stability was more closely correlated with hot water-extractable carbohydrate content than with total OC or hydrolysable (HCl) or NaOH-extractable carbohydrate contents. They concluded that hot water-extractable carbohydrate fraction may represent an important fraction for the formation of stable aggregates. For a clayey LAC soil of Antilles (site 8), Feller et al. (1991c) showed, using ultramicroscopic studies and metal-stained techniques (Thiery, 1967; Foster, 1981), that hot water extracted a large amount of the stained amorphous OM associated with clay matrix. This extract was very rich in HCl-hydrolysable carbon and its sugar composition was characterized by a very low (< 0.1) xylose to mannose ratio consistent with a microbial exudate origin for this fraction. A same tendency (low xylose / mannose ratio) was also observed (Feller, unpublished results) for a vertisol (site 9). This may emphasize the role of microbial PS origin in the stabilization of the structure of clayey tropical soils.

2. Studies on Water Stable Aggregates

The majority of studies on the organic composition of WSA generally deals with measurements of their OC and carbohydrate contents, and sometimes with their neutral sugar composition. Of course, other organic components have been studied, e.g. humic substances (Piccolo and Mbagwu, 1990).

The literature is rich in conflicting results for OC and carbohydrate contents as well as for sugar composition. In some studies, variations in OC and/or carbohydrate contents do not appear to follow a clear trend (Dormaar, 1987; Piccolo and Mbagwu, 1990). Tisdall and Oades (1980) reported for different plots on a red brown earth the following trend : high OC contents (1 to 2%) for > 250 μm, low OC contents (0.3 to 0.7%) for 20 to 250 μm and medium OC contents (0.7 to 1.7%) for < 20 μm aggregates. A decrease in OC and/or carbohydrate contents with a decrease in aggregate size was reported by Haynes and Swift (1990) for inceptisols (comparison of > 2.0 and < 0.25 mm), by Oades and Waters (1991) for a mollisol and an alfisol, and by Dormaar (1984) for a chernozem (size aggregates from 2.0 to 0.1mm). For a silt loam brunisol, Baldock et al. (1987) showed that the carbohydrate content remained constant for 8.0 to 1.0 mm aggregates but increased for lower aggregate sizes (1.0 to 0.1 mm). The same problems in variation appear in the comparison of the relative sugar composition (content of a single sugar in % of total sugar in each aggregate class) among different aggregate size classes. Dormaar (1984) did not find differences in the relative sugar composition between various aggregates. By contrast, Baldock et al. (1987) observed that in continuous bromegrass (*Bromus inermis* Leyss) the contribution of plant carbohydrates increased as aggregate size decreased, while in a continuous grain-corn (*Zea mays* L.) plot the reverse was noted.

For all these aspects, one problem encountered is that the studies generally do not take into consideration the mineral and organic heterogeneities in the composition of WSA, i.e. the mineral sand and the plant debris (or light) fractions. In order to interpret aggregate OM data, Elliott et al. (1991) proposed to correct the sand and organic light fractions of every aggregate size class. This was applied by these authors on a tropical cultivation chronosequence of Peruvian ultisols, and they demonstrated that the OC concentration of the 'heavy' fraction was, with few exceptions, not different among size classes or treatments. In the same way, Albrecht et al. (1992b) reported for a vertisol (site 9) and a clayey LAC soil (site 8) that the WSA obtained after 6 hours of end over end shaking presented about the same concentrations (20 mg C/g aggregate) for aggregate size ranging from 5 to 2000 μm when the light fraction was excluded. This might be also applied to the relative sugar composition of different aggregates for it was often shown, for temperate (Whitehead et al., 1975; Murayama et al., 1979; Turchenek and Oades, 1978; Cheshire and Mundie, 1981; Angers and Mehuys, 1990; Angers and N'dayegamiye, 1991) as well as for tropical soils (Feller et al., 1991c and unpublished results), that the *in situ* sugar composition of the size OM fraction varies systematically: a decrease in the xylose/mannose (or xylose + arabinose/galactose + mannose) ratio from the plant debris (or light) fraction to the organo-clay fraction. That decrease is consistent with a decrease in the participation of plant-PS (or an increase in the participating PS from microbial origin) in aggregate stabilization.

In conclusion, these apparently contradictory results have two main implications for soil structure research: (i) it is important to standardize the methodological and conceptual approaches to characterize the so-called 'water-stable aggregates;' and (ii) as water-stable aggregates are mixtures of mineral particles, particulate OM (plant and fungi debris) and organo-clay and silt complexes, research must be focused on aggregate composition in terms of size OM fractions. As the OMSF includes OC and mineral particle size distributions and the characterization of organic fraction of different qualities, it allows the direct studies of OM location in aggregates.

VI. Role of Soil Structure in the Stabilization of Soil OM

In the preceding section, we have seen that for a given pedological situation, the higher the OC content, the higher the structural stability. As a feedback effect, could a high aggregation stability stabilize OM? Two types of processes are usually invoked for the *in situ* stabilization of soil OM: (i) limitation of mineralization processes; and (ii) limitation of erosion processes. These two aspects will be now discussed for tropical situations.

A. Role in the Mineralization Processes

As outlined by Ladd et al. (1993), 'electron microscopy studies (SEM, TEM) have provided the visual evidence to reinforce conclusions drawn from other studies that physical protection mechanisms are important determinants of the stability of organic matter in soil.' Ultramicroscopic observations (TEM) of tropical vertisol under pasture (Figure 10) agree with this 'visual evidence:' plant cell wall debris, bacteria colonies or amorphous OM can be protected from decomposer organisms in microaggregates by a surrounding dense clay fabric. Diverse experimental approaches relevant to a physical protection of OM were recently reviewed by Ladd et al. (1993) for non-tropical situations. Their general conclusions are that in either increasing clay content and/or increasing structure stability, there are 'limitations in the accessibility of substrates to decomposer microflora and of microorganisms to microfaunal predators, by virtue of differences in their pore size location within aggregates.'

As both texture and structure affect the pore space and the pore size distribution in the soil, it is often difficult to distinguish between a 'texture effect' (clay or < 2 μm primary microaggregate contents) and an 'aggregation effect' (> 2 μm secondary stable aggregate contents) on the physical OM protection. Although enough significant data are lacking on these aspects for tropical situations we shall present some partial, indirect and perhaps contradictory results to illustrate the need of future research. We shall try arbitrarily to distinguish the 'texture effect' from the 'structure effect.'

1. The 'Texture Effect'

From Figure 2 it appears that clay content plays an important role in the storage of OC. For non-cultivated as well as for cultivated situation, the OC storage depends on the soil management and differs according to the soil OM size fraction (Figure 4). In *cultivated situations*, with a low aggregate stability, organic carbon storage is dependent on texture mainly for the organo-clay fraction, while OC contents of plant debris (20 to 2000 μm) and silt complex (2 to 20 μm) fractions are relatively constant in the range of the texture studied. There are no protective effects from the clay content on the > 2 μm fractions.

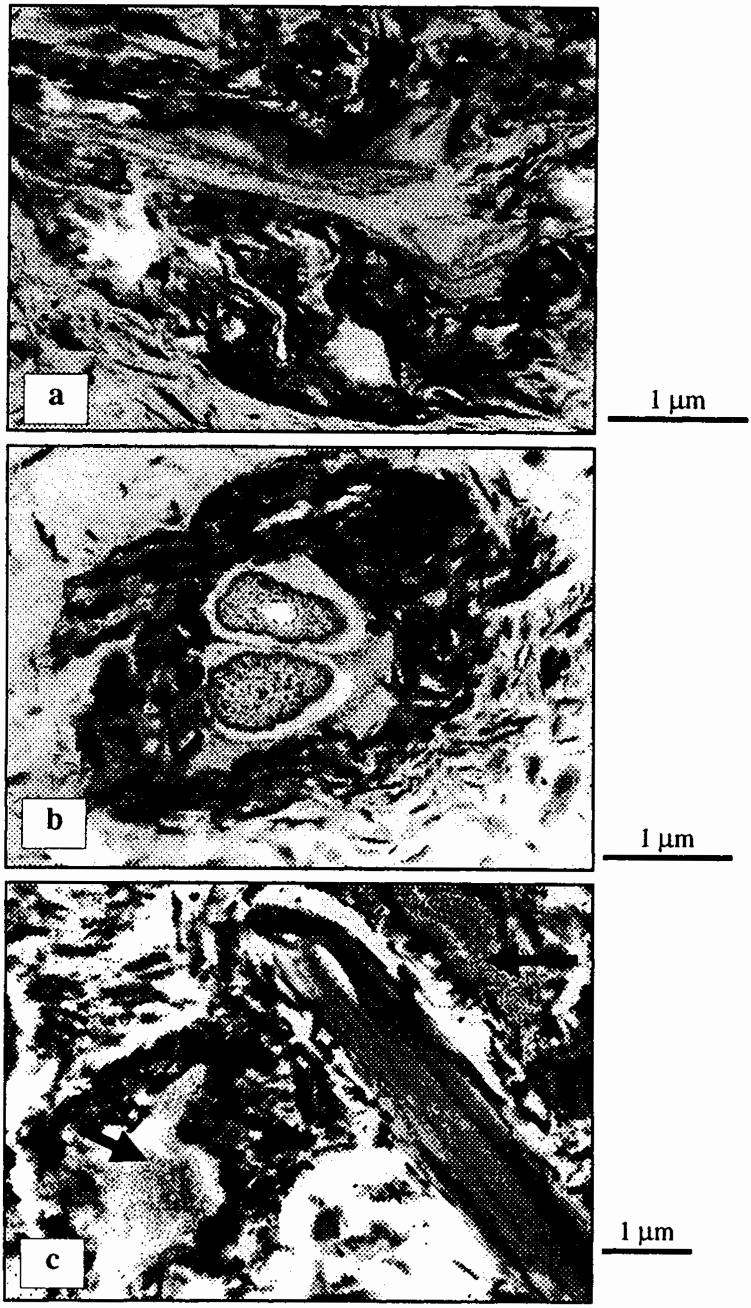

Figure 10. TEM of an ultrathin section of vertisol aggregates (site 9, pasture) showing (a) plant cell wall debris, (b) bacteria, (c) amorphous OM 'physically protected' by clays.

Similar results were obtained by Balesdent et al. (1991) for cultivated temperate soils. For *non-cultivated situations* (native vegetation, long-term fallows, artificial meadows), with a generally high aggregate stability, a trend is observed for an increase in OC content with clay content for all the size fractions, in particular for the plant debris fraction. Different hypotheses can be invoked to explain the increase in OC content of the plant debris fraction with clay content: (i) plant productivity and therefore OC inputs are higher in clayey soils than in coarse textured soils; and (ii) as the structural stability of rich in OC clayey soils is higher than that of coarse textured soils, the plant debris fraction can be protected in stable aggregates against mineralization. Moreover, a large fauna (earthworms) activity in non-cultivated clayey soils enhanced the stability of the structure.

Unfortunately, for the situations investigated in this chapter, the litter and root inputs to the soil were not quantified. Therefore, it is difficult to determine if the observed 'texture effect' may be due to differences in organic input levels or in a protection against mineralization (aggregation effect).

2. The 'Aggregation Effect'

The effect of aggregation on the accessibility of an agent (biotic or abiotic) to a substrate can be studied by the comparison of results obtained before and after disaggregation of a given soil sample. A different disaggregation status can be obtained by grinding the air-dried sample or dispersing it under water. We report results concerning the second approach, specifically the effect of aggregation on: (i) the accessibility to specific organomineral surface areas (SSA); and (ii) the mineralization of carbon (Cm) and nitrogen (Nm).

In both cases (SSA, C and N mineralization), measurements were conducted on the 'aggregated' soil 0 to 2 mm (bulk soil) and on its size OM fractions obtained after dispersion. Values for the 'dispersed' soil sample (sum of the fractions) were then calculated from the weight and the SSA, Cm and Nm of the separated fractions and compared to those of the 'aggregated' soil. An aggregation effect on the accessibility to SSA and mineralizable C and N might be expressed by the inequality: Bulk sample < Sum of fractions. SSA were measured from nitrogen gas adsorption isotherms (N_2-BET method) on LAC soils of sites 2, 8, 11, 12 (Feller et al., 1992) and Cm and Nm after 28 day aerobic incubations (Nicolardot, 1988) on soils of sites 1 and 8 (Feller, 1993). Data from site 1 (very poor sandy soil) gave a low value for Nm which can probably be attributed to losses of soluble and easily mineralizable organic N (Cortez, 1989) during the size fractionation. For the remaining soils, there does not appear from Figure 11a and 11b to be a clear positive effect of the dispersion of the soil sample on its SSA or mineralizable C and N :

$$\text{SSA bulk} = \text{SSA-Sum} \quad \text{and} \quad \text{Cm, Nm - bulk} \geq \text{Cm, Nm - Sum}$$

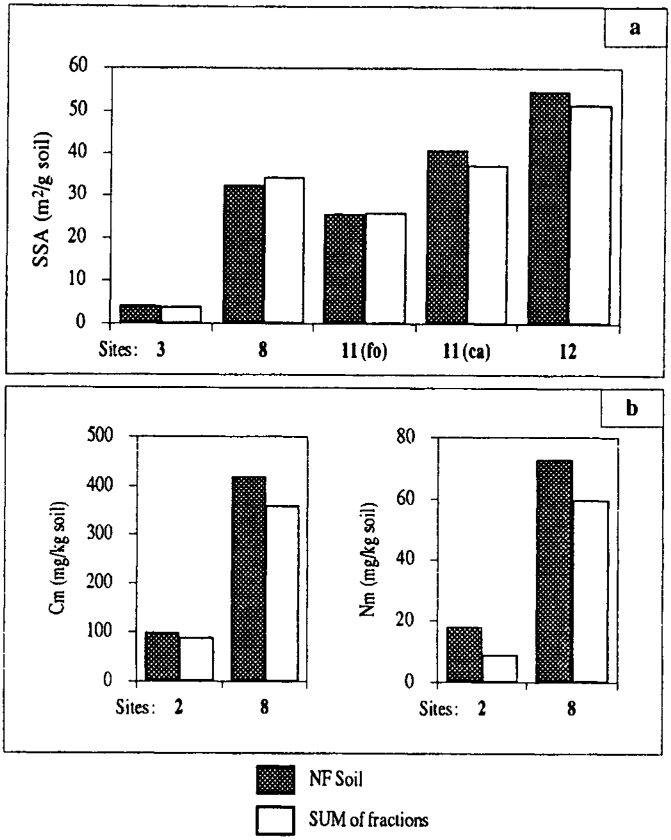

Figure 11. Effect of the dispersion of the soil on: (a) the accessibility of N_2 (BET-method) to organomineral specific surfaces (SSA) and (b) the quantities of carbon (Cm) and nitrogen (Nm) mineralized after 28 days incubation. The effect of dispersion is estimated by the comparison between the non-fractionated 0 to 2 mm soil sample (NF Soil) and the sum of size fractions obtained after dispersion (SUM). The site's number refers to Tables 1 and 2. For site 11, fo = forest and ca = 12-year sugarcane cultivation.

For these LAC soils, the destruction (without OM removal) of the secondary macro- and microaggregates (> 2 μm) does not reveal new organomineral surfaces. This is completely different from high activity clay soils where the N_2-BET external SSA is strongly dependent upon the mode of preparation of the sample (Feller, unpublished data). Similar results concerning the mode of preparation of the sample were observed on clay models (kaolinite, smectite) by Van Damme and Ben Ohoud (1990), and were already reported by Quirk (1978) from data of Fitzsimmons et al. (1970). This can be explained by the differences in the type of microporosity according to the clay mineralogy: always 'open' microporosity for kaolinitic soils or materials whatever the mode of preparation of the sample, both 'open' and 'closed' microporosity for smectitic samples. The ratio 'open'/'closed' is highly dependent on the hydric or ionic history of the sample (Tessier, 1991). Although there is a negligible effect of *secondary* aggregation on accessibility to organomineral surfaces, the comparison of cultivated (CULT) and non-cultivated (NCULT) sites of the clayey oxisol (8 Figure 10.a) indicate the possibility of an OM effect on SSA. However, the higher SSA for the cultivated sample is mainly due to a higher SSA of its fine and coarse clay fractions in relation to a lower carbon contents for these fractions (detailed results in Feller et al., 1992). Overall, it is only on the *primary* microaggregates scale ($< 2\ \mu m$) that an OM/aggregation effect can occur on the accessibility of N_2 to organomineral surfaces.

The results obtained here through mineralization experiments (Cm, Nm) seem to confirm the absence of a significant effect of aggregation on depressing OM mineralization. However, there are conflicting reports in the literature about this effect. For *tropical situations*, little or no effect was observed by Robinson (1967) and Bernhard-Reversat (1981). In contrast, an important effect of aggregation on C mineralization is reported by Martin (1992) and Lavelle and Martin (1992) for the casts of endogeic earthworms (*Millsonia anomala*) in an Ivory Coast alfisol. These authors show that after 400 days of incubation, the OC content of the earthworm casts was 20% higher than that of the control (non-ingested soil). This was attributed to the high compaction and stability of these casts (Blanchart, 1992; Blanchart et al., 1993). Moreover, the OMSF of samples show that differences between casts and control were mainly due to the plant debris fraction ($> 50\ \mu m$) which was protected from decomposition in the casts. This important result may explain the stabilization of the plant debris fraction ($> 20\ \mu m$) we also observed in the non-cultivated fine-textured soils (section VI.A.1. and Figure 5a). For a *subtropical oxisol*, Beare et al. (1994a, b) have clearly shown the protective effect of aggregation on soil C and N mineralization, with about 20% of SOM physically protected in water stable aggregates of the 0 to 5 cm soil layer, when soil was cultivated with no tillage management practices. In contrast, no effect was observed in soils under conventional tillage with lower OC contents and structural stability. For *temperate situations*, little or no effect of aggregation on C and N mineralization can be deduced from the results of Catroux and Schnitzer (1987) whereas Powlson (1980), Elliot (1986), Gupta and Germida (1988), Gregorich et al. (1989), Borchers and Perry (1992) and Hassink (1992) reported significant positive effects of disaggregation on C and/or N mineralization. This SOM protective effect of aggregation is generally relatively more important during the first days of incubation (Gupta and Germida, 1988; Gregorich et al., 1989) in fine textured soils than in the coarse textured (Borchers and Perry, 1992; Hassink, 1992) and sometimes (Gupta and Germida, 1988) for cultivated than for native soils.

In conclusion, on a *long-term scale* clay content appears as the main factor in the OC stabilization of non-eroded LAC soils, for cultivated as well as for non-cultivated situations. Whatever the soil management, OC stabilization occurs in the clay fraction, but a supplementary protective effect on plant debris fraction can appear in non-cultivated situations, probably due partly to the effect of the fauna on aggregation. This effect will be rapidly and largely reduced in many cultivated situations by the decrease of aggregate stability due to decreases in OM content and fauna activities. On a monthly or *seasonal scale*, our first results show that in LAC soils, secondary macro- and microaggregation (> 2 μm) by itself does not play an important role in the dissimulation of organo-mineral surfaces and in the C and N mineralization levels. On the other hand, on the primary microaggregate scale (< 2 μm), a significant part of the organo-clay surfaces can be protected from decomposition in the OC rich soil samples of the non-cultivated clay soils. It is clear that more systematic studies on tropical soils are necessary to ascertain which scale (size and time) of the protective effect of aggregation may be considered as important in regard to the mineralization processes.

B. Role in the Erosion Processes

The OC storage in tropical areas may be favored by diminishing the OC losses due to erosion and particularly sheet erosion (Roose, 1980/81; El Swaify and Dangler, 1982 ; Lal, 1982). For West Africa LAC soils, Roose (1977) measured the 'selective effect' of sheet erosion on fine element and nutrient losses (ratio of the composition of the eroded particles vs. composition of the 0 to 5 or 0 to 10 cm soil layer). For the OC content the selective ratio ranged between 1.5 to 12.8; while for the weight of the 0-2 μm fraction, it averaged from 1.1 to 6.0.

The higher the aggregate stability, the lower might be the soil erodibility. For instance, De Vleeschauwer et al. (1979) indicated that soil erosion (measured by rainfall simulator) and detachability (according to De Leenheer and De Boodt, 1959) were both determined by OC content (and CEC). Therefore, there exists a complex interaction between OC storage and aggregate stability: OC plays a major role in the stabilization of aggregation but aggregation can reinforce the OC storage by diminishing OC losses by sheet erosion. These aspects are illustrated with some recent results obtained on a vertisol (site 9) and a clayey LAC soil from Antilles (Albrecht et al., 1992b and unpublished data). The soil OC contents of the different plots in this study differed in relation to their historical land use and soil management practices: pasture (rich in soil OC) or market-gardening (poor in soil OC), the duration of the cropping system, and the degree of management intensification (irrigation, fertilization and duration of intercropping spontaneous fallows).

As OC content varies from 15 to 50 g C/kg soil in the 0 to 5 cm layers (Figure 12), these plots represent suitable field models to study the effect of OC on the physical behavior of surface soil. Field rainfall simulation was studied on

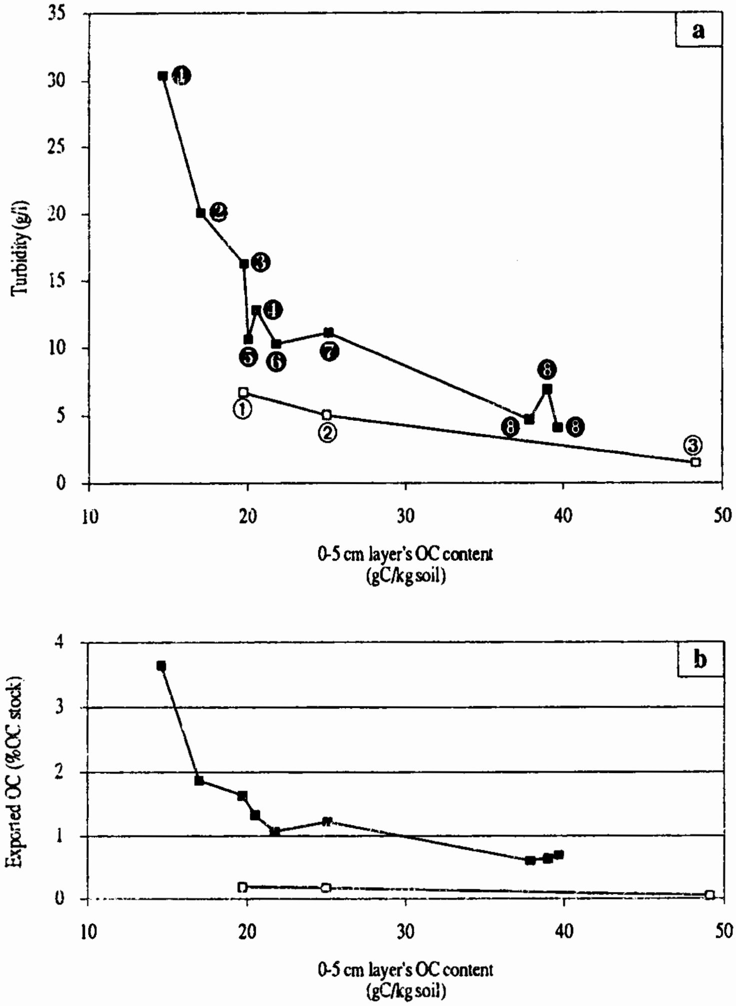

Figure 12. Relations between the OC content of the upper horizon and (a) the turbidity (obtained under rainfall simulation on 1 m^2 plots; rainfall and runoff intensities = 150 mm/h; the soil surface -hand ploughed- is the same in all the situations) and (b) the exported OC. Black signs are situations on vertisols (site 9): ❶ long-term market gardening, ❷ one-year spontaneous fallow after long-term market gardening, ❸ 3-year spontaneous fallow after long-term market gardening, ❹ 2-year cropping after long-term artificial meadows, ❺ 2-year artificial meadow after long-term market gardening, ❻ 4-year artificial meadow after long-term market gardening, ❼ 6-year artificial meadow after long-term market gardening, ❽ long-term artificial meadow. White signs are situations on ferrallitic soils (site 8): ① long-term market gardening, ② one-year spontaneous fallow after long-term market gardening, ③ long-term artificial meadow.

each plot as described in section III.C.2. Figure 12a clearly shows that for vertisol the runoff water turbidimetry was highly dependent on the OC content of the 0 to 5 cm layer. In all cases a selective exportation of fine elements was observed. When expressed in terms of percentage of exported OC (Figure 12b), the higher the OC content of the 0 to 5 cm layer, the lower the percentage of exported OC. For the clayey LAC soil (ferrallitic), the exported OC is much lower. On a medium to long-term scale (c.a. 10 years of intensified market-gardening), such sheet erosion on vertisol leads to a very low OC content (about 12 g C/kg soil) for a clayey soil, whereas the clayey LAC soil with the same cropping system displays a much higher OC content (18 g C/kg soil).

VII. Concluding Remarks

In tropical areas, the clearing of the native vegetation followed by cultivation is accompanied in LAC and HAC soils by rapid declines in SOM content and structural stability. Organic fractions involved in the observed variations in soil aggregation and aggregate stability were strongly related to soil texture: the plant debris fraction for coarse-textured soils, the plant debris and organo-clay fractions for fine-textured soils. The consequences in terms of aggregate stability were discussed in relation to water stable macro- and secondary microaggregates. This review has also demonstrated the use of multi-sieving and kinetic approaches for the WSA characterization of the studied tropical soils. In comparison with mollisols or alfisols in temperate areas, tropical soils exhibit only a low tendency towards an 'aggregate hierarchy' because the dispersion processes (rapid dispersion of clay particles or clay size microaggregates) are generally more important than the disaggregation processes (division of macroaggregates in smaller aggregates according to the increasing of disruptive energy).

Although the role of SOM in the stabilization of the soil structure in tropical soils is well documented, it lacks data to evaluate the effect of macro- and/or secondary microaggregation on OM storage by the protection of OM against mineralization. Some results such as electron microscopic observations or increase in the plant debris fractions with increase in the stability of the structure, or those of Beare et al. (1994b) on a subtropical oxisol, might agree with such an effect, while other results (for LAC soils) based on tests of disaggregation to study the accessibility to organo-mineral surfaces (SSA) or to mineralizable carbon and nitrogen (Cm, Nm), do not support the concept. Generally, the main important and evident effect of aggregation on OM storage was due to its positive effect on reducing soil erodibility, especially the limitation in OM losses by sheet erosion.

To address these different aspects, much research is needed to characterize the diverse relationships between soil structure and OC storage in LAC and HAC tropical soils. The following questions need to be answered:

(i) Does there exist a significant effect of aggregation on the protection of OM against mineralization? On what scale does this protection occur (macro-, secondary micro- or primary microaggregates) and what type of OM is involved (plant debris, amorphous fraction, etc) and for what type of soil (LAC, HAC)?

(ii) Do aggregates which differ in their stability, also differ in their OM composition? Which are the size OM fractions and/or the specific binding organic constituents involved?

(iii) Does there exist a threshold value for the SOM content or SOM fraction that might be significant in terms of erodibility of soils?

To answer these different questions, it is necessary to develop systematic approaches in terms of:

(i) Definition of the so-called water stable aggregates (WSA),

(ii) Location of OM within the WSA. For this the use of optic and electron microscopic techniques is necessary and the characterization of SOM by size fractionation besides chemical analysis might be powerful.

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