Soil Organic Matter Dynamics and Sustainability of Tropical Agriculture
Edited by K. Mulongoy and R. Merckx

A Wiley-Sayce Co-Publication

# 2.1

# Organic inputs, soil organic matter and functional soil organic compartments in low-activity clay soils in tropical zones

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Summary

Low-activity clay soils are widely distributed in the inter-tropical zone. Quartz, kaolinite, iron and aluminium oxide minerals tend to be dominant in these soils and thus many soil properties of the surface horizons depend largely on the soil organic matter content; clearing natural vegetation and cultivation result in significant decreases in organic matter, especially for annual crops. Therefore, more research needs to be carried out on characterizing soil organic matter, its dynamics under different soil management practices and its relationship with other soil properties. The study described in this paper examined the ecological and agronomic factors which determine organic matter content of the surface horizons, the organic matter fractions involved in the observed variations, and the functions of these fractions with regard to nutrient cycling.

Low-activity clay soils (ferrugineous and ferrallitic soils, according to the French classification system) are common throughout the inter-tropical zone. Quartz, kaolinite, iron and aluminium oxide minerals tend to be dominant in such soils and thus many physical, chemical and biological soil properties of the surface horizons depend largely on the soil organic matter content (Boissezon, 1973; Boyer, 1982; Pieri, 1989; Feller et al., 1992). In addition, natural vegetation clearing and crop cultivation results in a significant decrease in organic matter, especially for annual crops. Charreau and Nicou (1971) and Pieri (1989) have demonstrated the need for good management of soil organic matter in order to maintain sustainable agricultural systems in this zone. In essence, there needs to be more research on the characterization of soil organic matter, its dynamics under different soil management practices and its relationship with other soil properties. The study described in this paper focused on:

- the ecological and agronomic factors which determine the soil organic matter content of the surface horizons of low-activity clay soils;

- the soil organic matter fractions involved in the observed variations;
- the functions of these fractions with regard to nutrient cycling.

## MATERIALS AND METHODS

The study dealt with surface horizons only. Some characteristics of the soils used in the study are presented in Table 1. The sites samples were in West Africa (labelled 1, 2, 3 and 4 in the table), the West Indies (5, 6 and 7) and Brazil (8). All the soils from West Africa had been cultivated under low-input, traditional systems. Only sites showing minimal erosion or hydromorphological effects were selected. None of the soils contained gravel material in the surface horizons. Soils were sampled with a gauge to the depth of 0-10 cm and 10-20 cm. Each determination was carried out on an average sample obtained from 6 to 12 replicates.

**Table 1 General characteristics of selected sites**

| Study sites and references[a] | Vegetation[b] | Mean annual temperature (°C) | Mean annual rainfall (mm) | Soil (0-10 cm) Type[c] | 0-2 µm (g/100 g) | C (g/100 g) | C/N | CEC (pH 7.0) (cmol/kg) |
|---|---|---|---|---|---|---|---|---|
| 1 (Senegal) | Fa, CC | 29 | 600 | Ft | 3 | 0.3 | 10 | 2 |
| 2 (Senegal) | S, CC | 29 | 800 | Fl | 8 | 0.9 | 15 | 5 |
| 3 (Togo) | F, Fa, CC | 27 | 1040 | Ft | 9 | 1.2 | 12 | 5 |
| 4 (Ivory Coast) | S | 28 | 1360 | Fl | 12 | 1.2 | 16 | 8 |
| | S, Fa, CC | 28 | 1360 | Fr | 19 | 1.7 | 17 | 12 |
| 5 (Guadeloupe | Pa, CC | 25 | 3000 | Fr | 61 | 3.4 | 10 | 13 |
| 6 (Martinique) | F, S, CC | 26 | 1820 | Fr | 49 | 4.4 | 13 | 18 |
| 7 (St Lucia) | Fa, CC | 25 | 2700 | Fr | 54 | 3.0 | 14 | 14 |
| 8 (Brazil) | F, CC | 21 | 1200 | Fo | 50 | 3.6 | 10 | 10 |

Note: a 1 = Charreau and Nicou (1971); 2 = Feller and Milleville (1977); 3 = Poss et al. (1984); 4 = HYPERBAV (1990); 5, 6 and 7 = CEE (1988); 8 = Cerri et al. (1991).
b F = forest; S = savanna; Pa = pasture; Fa = fallow; CC = continuous cultivation after savanna or forest clearing.
c FAO classification system: Ft = cambic Arenosol; Fl = ferric Lixisol; Fr = ferric Acrisol (3, 5) and ferralic Cambisol (5, 6, 7); Fo = rhodic Ferralsol. French classification system: Ft = sol ferrugineux tropical peu lessivé; Fl = sol ferrugineux tropical lessivé à tâches et concrétions en profondeur; Fr = sol ferrallitique faiblement désaturé; FO = sol ferrallitique fortement désaturé (à caractère oxique).

### Organic matter fractionation

The factors determining the choice of fractionation method are discussed later in this paper. The method is based on a particle size fractionation (Feller et al., 1991a) of a soil previously dispersed with a sodic resin (Amberlite IRN 77). Between 20 g and 40 g of soil were shaken for 2-16 hours with 300 ml water and 100 ml resin (amount of soil and length of time shaken depended on the clay content of the sample). The suspension was sieved at 200 µm, 50 µm and 0-50 µm; the 0-50 µm suspension was sonified, to allow a better dispersion of the clay and silt fraction (Balesdent et al., 1991), before sieving at 20 µm. Fine silt (2-20 µm) was then separated from clay (0-2 µm) by sedimentation, and fine clay separated from coarse clay by centrifugation of the clay suspension.

The following solid fractions were obtained: 200-2000, 50-200, 20-50, 2-20, 0.2-2 and 0-0.2 µm, together with a solution (water was used for the fractionation) termed the 'W' fraction. In order to simplify the presentation of the results, these fractions were grouped into: 20-2000, 2-20 and 0-2 µm. In this study, the W fraction is considered to be negligible because of its low C and N content.

All the analytical determinations were done on samples dried at 50°C until constant weight was achieved. Total C and N content were determined on soils and fractions using a CHN analyzer (Carlo Erba model 1106).

### Mineralization of the particle size fractions

A sandy soil (site 1) and a clay soil (site 6) were compared for their content of mineralized C and N derived from the bulk samples (0-2 mm) or their particle size fractions.

For the whole soil (0-2 mm), 25 g were moistened at 80% of their field capacity (pF 2,5) and incubated in 125 ml flasks for 28 days at 28°C. Mineral N was extracted at 0 and 28 days with 1 M KCL; the method described by Nicolardot (1988) was used to determine $N\text{-}NH_4^+$, $N\text{-}NO_3^-$ and $N\text{-}NO_2^-$. Evolved $C\text{-}CO_2$ was measured at 0, 2, 7, 14, 21 and 28 days (Nicolardot, 1988). For size fractions, the 20-2000 µm fraction was incubated alone but each of the 2-20 and 0-2 µm fractions were mixed (1/1, w/w) with coarse commercial sand. The incubation conditions were similar to those applied to the whole soil. All determinations were conducted in triplicate.

## RESULTS AND DISCUSSION

### Factors determining organic matter content and variation

A number of environmental factors (such as temperature, rainfall, vegetation, erosion, hydromorphology, soil texture, mineralogy and land use) directly or indirectly influence the level of soil organic matter in tropical areas (Jenny et al., 1948; Laudelout et al., 1960; Theng et al., 1989). As noted by Elliot et al. (Paper 3.10, *these proceedings*): 'Seldom do we find these factors acting alone but they interact in complex ways.' However, if we exclude the mountainous tropical areas and include only low-activity clay soils showing minimal erosion and good drainage (in the top 50 cm), the main factors to consider are rainfall, soil texture and soil management. In non-mountainous tropical areas the temperature is generally higher than 21°C; under these conditions, the results reported by Laudelout et al. (1960) indicate a minor effect of temperature on soil organic matter content. Even within such parameters, very large surfaces of cultivated area or virgin lands are taken into consideration.

On 59 plots at the eight sites, regression analyses between C content in the 0-10 cm horizon (C), precipitation (P) and soil texture (0-20 µm) were performed (*see* Figure 1 *overleaf*). They show that, despite a wide range of precipitation, C content is not highly correlated with P ($r^2 = 0.38$). For example, site 4, which corresponds with a small watershed (1.4 $km^2$, P = 1360 mm) exhibits the whole range of C variations observed at all sites.

As shown in Figure 1 (b), there was a very close relationship between C and soil texture ($r^2 = 0.801$, $n = 59$). This correlation was not significantly increased ($r^2 = 0{,}805$) by a simple regression between C, fine elements (0-20 µm g/100 g) and precipitation (P mm). The following equation was obtained:

$$C\ (\text{mg/g soil}) = 0.47\ (0\text{-}20\ \mu m\ g/100g) + 0.002\ (P\ mm) - 1.74$$

This 'texture effect' confirms the results obtained by Jones (1973) using 605 savanna soil samples (0-15 cm horizons) collected in West Africa, and by Lepsch et al. (1982) for sugarcane sites in Brazil.

**Figure 1** **Relationships between C content and precipitation (a) and C content and soil texture (b and c)**

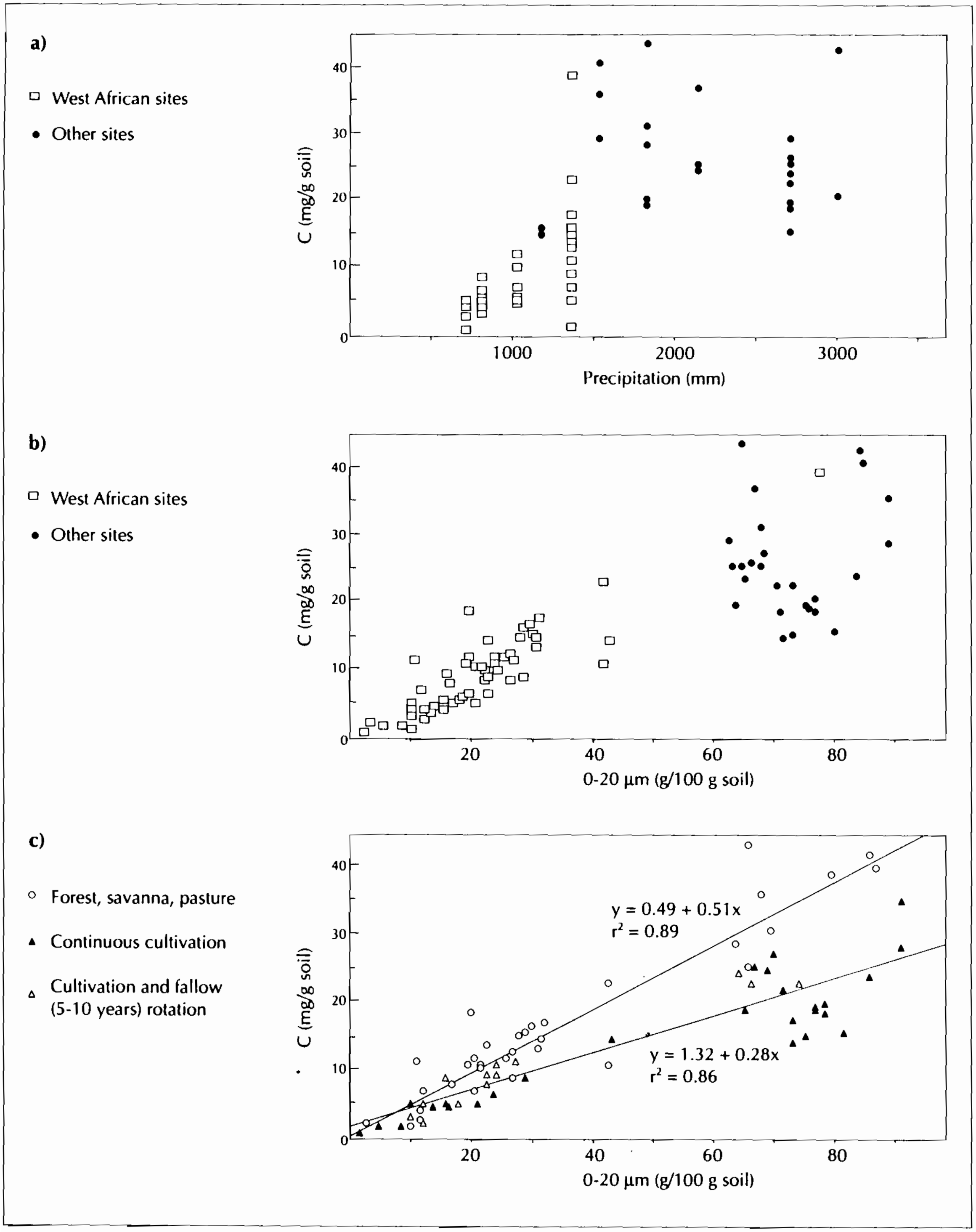


Figure 1 (c) illustrates a 'global cultivation effect'. It appears that the variation of C content depends upon the soil management practices and becomes more important when the clay + silt content increases. Soil organic matter content under annual crops was approximately 60% of that under natural vegetation. Sites after a fallow (about 5 years), receiving organic amendments or organo-mineral fertilization, presented a soil organic matter content intermediate between that of natural vegetation and that of continuous annual crops. After a long period of annual crops, pastures were very efficient in restoring soil organic matter levels within 5-10 years.

What soil organic matter fractions are involved in these variations? Before answering this question, it is necessary to choose an appropriate method for soil organic matter characterization.

## Nature and dynamics of organic matter fractions

*Size fractionation*

For over a century, soil organic matter has been characterized by chemical fractionation (acido-alkaline extraction, acidic or alkaline hydrolysis), with some interest being shown in pedogenesis research but with few significant applications in the field of agropedology. There are two possible reasons for this:

- humic substances generally have a low turnover (Anderson and Paul, 1984; Duxbury et al., 1989) and are therefore not necessarily implicated in the short-term processes (from a day to a decade) generally studied in cultivated situations;
- the functions of these chemical compartments in relation to major soil processes such as aggregation, mineralization and surface properties are not yet well established.

Thus, over the past two decades, more and more research on soil organic matter characterization has been based on physical (particle size and density) fractionation (e.g., Feller, 1979; Turchenek and Oades, 1979; Anderson et al., 1983; Tiessen and Stewart, 1983; Tiessen et al., 1984; Elliott and Cambardella, 1991). However, for tropical soils it is possible to distinguish three types of soil organic matter by simple particle size fractionation with water (Feller et al., 1991a):

- a 'plant debris' fraction (> 20 µm) consisting mainly of more or less recognizable, decomposed plant debris, with a C/N ratio higher than 15;
- an 'organo-clay' fraction (0-2 µm) made up of amorphous organic material (closely associated with clay) and of bacterial debris and metabolites, with a C/N ratio lower than 10;
- an 'organo-silt' complex (2-20 µm), the characteristics of which are variable and intermediate between the plant debris and the organo-clay fractions. Its characteristics are related to soil type, total soil organic matter content, micro-aggregation stability and the efficiency of the fractionation method in dispersing clay particles. This fraction is often rich in fungal debris, with a C/N ratio ranging from 10 to 15.

Figure 2 (*overleaf*) presents the average C/N ratio of the particle size fractions of 28 samples from West African low-activity clay soils. Figure 3 (*overleaf*) shows the percentage of the samples' total C and N content represented by these fractions. It should be noted that the C/N ratios of the clay fractions were significantly different from the 2-20 µm and 20-2000 µm fractions, reflecting different pathways of humification; the plant debris fraction represented a non-negligible percentage of the total C and N (30% and 20%).

**Figure 2 Mean values and standard deviations of C/N ratios in the different particle size fractions in West African soil samples**

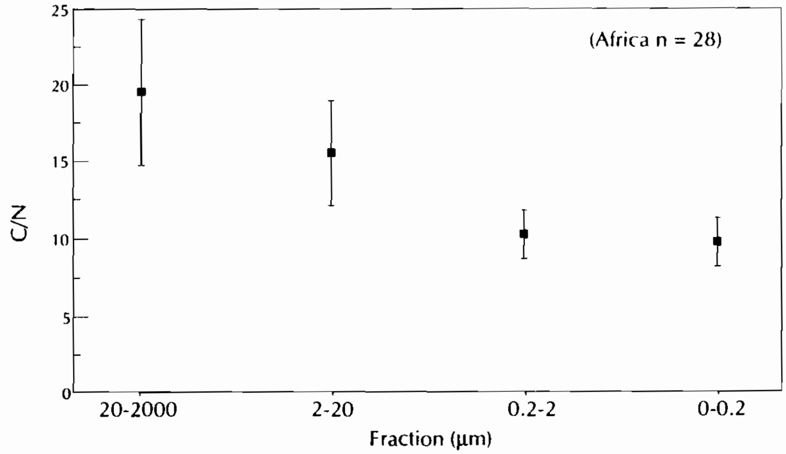
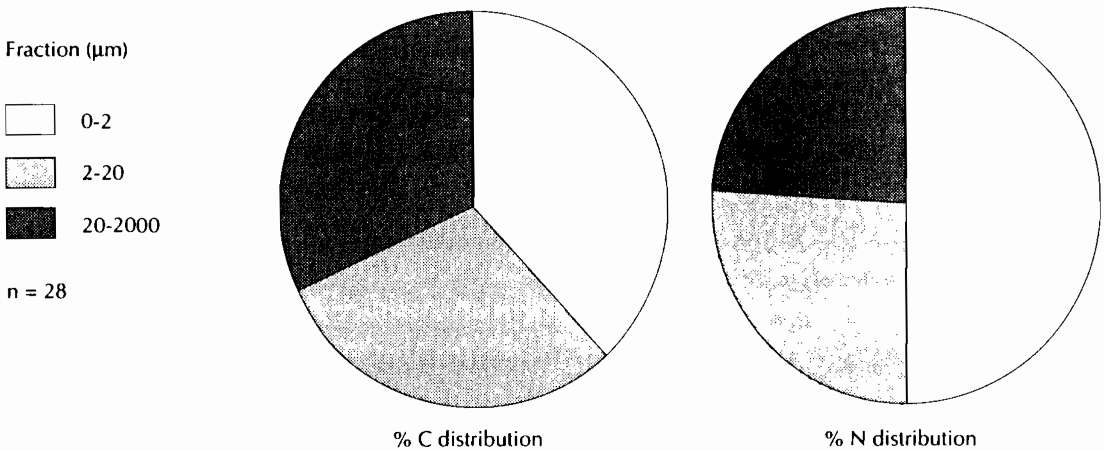



**Figure 3 C and N distribution within the particle size fractions in West African soil samples**



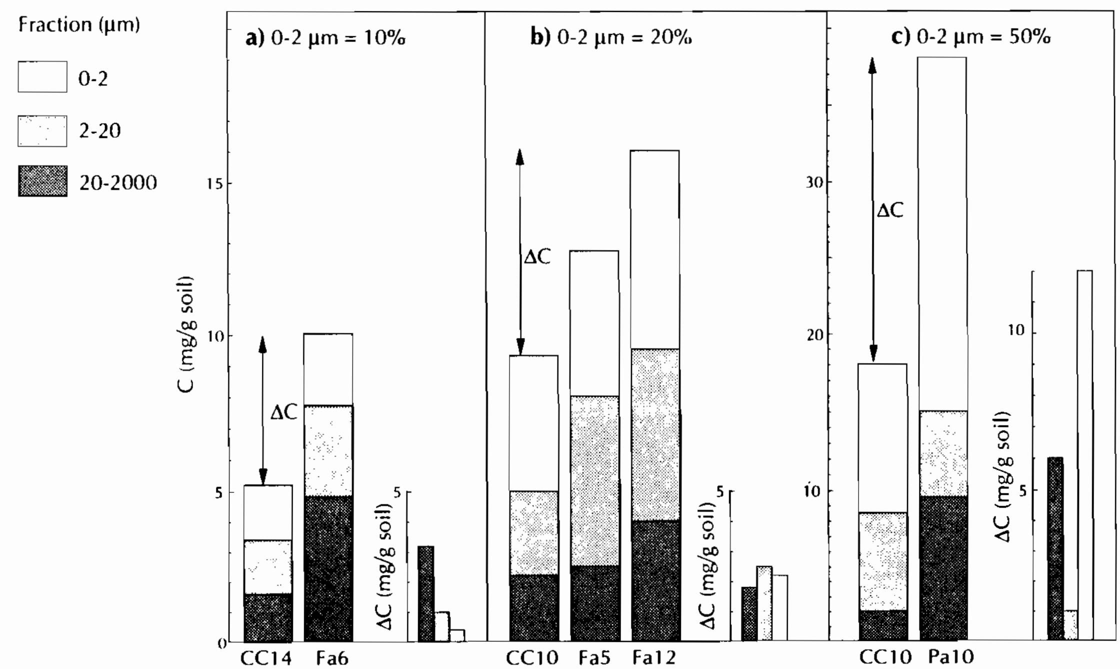

The particle size fractions also differ according to their neutral sugar composition (Whitehead et al., 1975; Turchenek and Oades, 1979; Cheshire and Mundie, 1981; Barriuso et al., 1985; Angers and Mehuys, 1990; Cheshire et al., 1990). Usually, soil organic matter associated with sands (or the 'light' fractions) is relatively rich in xylose and arabinose and low in mannose and rhamnose in relation to its plant residue origin. The organo-clay fraction, however, is relatively rich in mannose and rhamnose. Murayama (1984, 1988) suggested that the xylose/mannose ratio is a good index of the relative origin (plant heritage or microbial synthesis) of soil organic matter. We found that in a clay ferrallitic soil cultivated with sugarcane for over 50 years, this ratio was 43, 22 and 2.6 for leaves, roots and root exudates, respectively, the ratio of the different size fractions ranging from 3.0 for the 20-2000 μm fraction to 0.8 and 0.4 for the 2-20 μm and 0-2 μm fractions, respectively (Feller et al., 1991b).

*In situ dynamics of organic matter fractions*

The size fractionation method was applied to different tropical cropping systems (annual plants). For each system, the effect of soil texture was studied (Feller et al., 1991c). The systems selected were: the clearing-cultivation succession (clearing savanna or forest before continuous cultivation); and the cultivation-fallow (or pasture) succession.

The effect of fallow or pasture on soil organic matter fractions after long periods of continuous cultivation (of either food crops or vegetable crops) is presented in Figure 4. It is interesting to note from the results that soil texture played the major role not only in the storage of total soil organic matter, but also in the relative

**Figure 4 Effect of fallow or pasture after continuous cultivation on C content and the different particle size fractions at a) site 3, West Africa, b) site 4, West Africa and c) site 5, West Indies**




C = carbon; CC = continuous cultivation (10 and 14 years); Fa = fallow (5, 6 and 12 years); Pa = pasture (10 years)
ΔC (mg/g soil) = the differences between a) CC14 and Fa6, b) CC10 and Fa12 and c) CC10 and Pa10

variations of soil organic matter within the different size fractions. In the coarse-textured soils, the increase in C content after fallow periods was significant mainly in the plant debris fraction, followed by the organo-silt fraction, and only to a very slight extent in the organo-clay fraction. In the fine-textured soils, the increase in C content was significant in both the plant debris and the organo-clay fractions. Similarly, the results showed that in the clearing-cultivation succession the observed decrease in soil organic matter content was attributable to the plant debris fraction in the sandy soil and to the organo-clay fraction in the clay soil. For soil organic matter dynamics and biogeochemical processes, these results highlight the importance of these fractions in these soil types.

The importance of the plant debris fraction as an 'active' fraction is confirmed by its high turnover rate estimated by the $\partial^{13}C$ approach. This approach has been used by several authors, in both tropical zones (Cerri et al., 1985; Martin et al., 1990; Desjardins, 1991) and temperate zones (Balesdent et al., 1987, 1988).

In conclusion, morphological studies (optic and electronic microscopy), chemical determinations (C, N and sugar composition) and results of the *in situ* dynamics of soil organic matter fractions can be advanced in an attempt to extend the *reality* of these fractions to the *concept* of soil organic matter compartments, which could be valuable in simulation modelling (e.g., for the CENTURY model devised by Parton et al., 1987).

## Biogeochemical functions of particle size fractions

Few studies have been conducted, even for temperate zones, to assess the functions of the soil organic matter fractions with regard to nutrient cycles. Here we report some preliminary results concerning short-term C and N mineralization (Feller and Nicolardot, in prep.).

Tests of C and N mineralization (28 days) were conducted on a sandy soil (site 1) and a clay soil (site 6), using unfractionated samples (0-2 mm) and different size fractions (*see* Table 2).

**Table 2 C and N mineralization in a sandy soil (Ft) and a clay soil (Fr) after 28 days incubation, and the corresponding particle size fractions**

| | | C mineralization | | | N mineralization | | |
|---|---|---|---|---|---|---|---|
| Soil | Fraction (μm) | μg/g soil | % of sum | % of WS[a] | μg/g soil | % of sum | % of WS |
| Ft | 20-2000 | 88 | 86 | | 2.8 | 43 | |
| | 2-20 | 3 | 3 | | 1.0 | 15 | |
| | 0-2 | 11 | 11 | | 2.8 | 42 | |
| | Sum | 102 | 100 | 84 | 6.6 | 100 | 43 |
| | WS | 122 | | 100 | 15.2 | 245 | 100 |
| Fr | 20-2000 | 108 | 32 | | 1.9 | 3 | |
| | 2-20 | 33 | 10 | | 0.9 | 11 | |
| | 0-2 | 199 | 58 | | 54.3 | 86 | |
| | Sum | 340 | 100 | 78 | 61.1 | 100 | 84 |
| | WS | 434 | 128 | 100 | 72.5 | 119 | 100 |

Note: a WS = whole soil.

If we compare the total C or N mineralization recovered from different fractions with that of the unfractionated sample (100%), the following data are obtained:

- for C mineralization, 83 and 78% for the sandy and clay soils, respectively;
- for N mineralization, 43 and 84% for the sandy and clay soils, respectively.

The low value obtained for N mineralization with the very poor sandy soil (43%) is probably attributable to losses of soluble and easily mineralizable organic N (Cortez, 1989) during the size fractionation. (The W fractions were not studied). It is important to note that mineralization of C and N was always lower for the sum of the fractions than for the unfractionated sample; hence, aggregation does not exert a depressive effect on soil organic matter mineralization. There are conflicting reports in the literature on this issue. Little or no effect was observed by Robinson (1967) and Bernhard-Reversat (1981), whereas Elliott (1986), Gupta and Germida (1988) and Gregorich et al. (1989) reported a significant depressive effect.

Regarding the amounts of C and N mineralized from each size fractions, it appears that in the sandy soil, low in soil organic matter, significant amounts of mineralized C and N originated from the plant debris fraction. However, in clay soil, rich in soil organic matter, 58% and 86% of the mineralized C and N originated from the organo-clay fraction. A similar trend was observed by Chichester (1969), Cameron and Posner (1979), Lowes and Hinds (1983), Sollins et al. (1984) and Catroux and Schnitzer (1987). These results concur with those of Blondel (1971) and confirm that, in the short-term, the plant debris fraction plays an important role in the biogeochemical processes, at least in sandy soil. It is also clear that an 'active' soil organic matter fraction is associated with clays, probably as microbial biomass, microbial metabolites and/or root exudates. This assumption agrees with the electronic microscopy observations of the clay fraction for the soil of site 6 (Feller et al., 1991b), the results reported by Chotte et al. (Paper 1.2, *these proceedings*), and other data recorded for temperate soils (McGill et al., 1975; Ladd et al., 1977a, 1977b).

## CONCLUSION

Some general conclusions concerning soil management and research needs may be drawn from these results. In terms of soil management, for all types of soils it is clear that the plant debris fraction plays an important role in the short term (from a few months to a few years). This time scale is relevant to cultivated plot management. For sandy soils in particular, it is necessary to promote plant debris restitution through organic amendment application or through root restitution in an adapted cropping succession: short (managed) fallows, agroforestry, grass-legume pastures, and perennial or annual crops with a well-developed root system (Pieri, 1989; Sanchez et al., 1989). In terms of research needs, the results indicate that it is important to improve our understanding of the nature and dynamics of soil organic matter associated with clay, especially to identify and/or separate the organo-clay subfraction with a high turnover rate, and that the approach described in this paper should be extended to studies of the relationship between the particle size soil organic matter fractions and other fundamental biophysical or biogeochemical soil processes.

### Acknowledgements

The author is grateful to M.J. Tartarola for typing the manuscript and to an anonymous reviewer for his/her helpful comments.

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