CHARACTERISATION AND DYNAMICS OF ORGANIC MATTERIN LOW ACTIVITY CLAY SOILS IN WEST AFRICA.

CARACTÉRISATION ET DYNAMIQUE DE LA MATIÈRE ORGANIQUE DANS QUELQUES SOLS FERRUGINEUX ET FERRALLITIQUES D'AFRIQUE DE L'OUEST.

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Abstract.

The effects of climate, soil texture and cultivation on organic matter (OM) content and dynamics were examined in West African low activity clay soils. Results were compared to those obtained on soils from the West Indies and Brazil. These sites differed widely in their climate and especially their rainfall which varies from 600 to 3000 mm.

It was shown that:
-organic matter contents of cultivated or non cultivated soils were largely dependant on the texture and much less on the climate. The decrease of organic matter due to cultivation was about 30 to 40% of the initial level and was faster in sandy soils (3 years) than in clayey soils (10 years);
-the specific fractions of organic matter undergoing decreases in clearing-cultivation succession or increases in cultivation-fallow succession varied with soil texture. In sandy soils most of the changes in organic matter occurred in the coarse plant debris (20-2000 µm) and fine silt (2-20 µm) fractions, whereas for the clayey soils most of the variations occurred in the clay fraction (0-2 µm).

In terms of biogeochemical processes these results emphasise the importance of the plant debris compartment in coarse textured soils and of the organo-clay complexes in the clayey soils. Agronomical aspects of soil organic matter management are discussed.

Résumé

On étudie l'effet de la texture sur les stocks et la dynamique sous cultures des matières organiques (MO) d'horizons de surface de sols ferrugineux et ferrallitiques (bien drainés) d'Afrique de l'Ouest en comparaison avec des situations du Brésil et des Antilles. On constate que:
- les stocks organiques des sols, cultivés ou non, sont beaucoup plus déterminés par la texture que par le climat, malgré le fort gradient pluviométrique considéré (600 à 3000 mm). Avec la mise en culture, on assiste, entre 3 et 10 ans à une diminution de 30 à 40% du stock organique, diminution d'autant plus rapide que le sol est plus sableux;
- aussi bien pour les successions "végétation naturelle-culture " (diminution de MO) que "culture-jachère" (augmentation de MO), les sols sableux s'opposent

aux sols argileux quant aux formes de MO concernées par les variations de stocks organiques observées: essentiellement les débris végétaux (fraction 20-2000 µm) et le complexe organo-limoneux (2-20 µm) pour les sols sableux, essentiellement le complexe organo-argileux (fraction 0-2 µm) pour les sols argileux.

Ces résultats mettent l'accent sur l'importance du compartiment "débris végétaux" dans le fonctionnement biogéochimique des sols sableux à sablo-argileux, largement représentés en Afrique de l'Ouest, et de celui des MO associées aux fractions 0-2µm dans les sols argileux.

Introduction.

Low activity clay soils are widely distributed in West Africa (Boulet et al., 1971), quartz, kaolinite, iron and aluminium oxides being the dominant minerals. In these soils, organic matter has an important role in the determination of soil properties (Boissezon, 1973; Boyer, 1982). For the surface samples of West African soils studied in this paper some properties as pH H_2O, nitrogen (N), total and available phosphorus(P), exchangeable bases (EB) and cation exchange capacity (CEC) are shown to be better correlated to total carbon than to the clay plus silt content (0-20 µm) (table 1). Charreau and Nicou (1971) and Pieri (1989) point to the necessity to manage the soil organic matter properly to maintain a sustainable agriculture in this area. Therefore it appears essential to develop research on the characterisation of organic matter, on its dynamics under different soil management practices, and on its relation with other soil properties.

Table 1. Multiple regression between a soil property (Y) of low activity clay soils and the carbon (C $mg.g^{-1}$) and clay + silt (0-20; µm $g.100g^{-1}$) contents. Horizons 0-20 cm. West African sites.
Tableau 1. Régression multiple entre une propriété (Y) des sols ferrallitiques et ferrugineux et les teneurs en carbone (C $mg.g^{-1}$) et en éléments fins (0-20 µm; $g.100g^{-1}$). Horizons 0-20 cm. Situations d'Afrique de l'Ouest.

Y	n	r	r_1(*)	r_2(**)
pH-H_2O	32	0.46	0.46 HS	0.38
N	32	0.96	0.96 HS	0.63 HS
total P	32	0.67	0.67 HS	0.51 HS
available P	24	0.55	0.37	0.12
E.B. (pH 7.0)	32	0.74	0.70 HS	0.36
C.E.C (pH 7.0)	32	0.93	0.93 HS	0.72 HS

(*) Correlation Y = f(C $mg.g^{-1}$)
(**) Correlation Y = f(0-20µm $g.100g^{-1}$)
(***) HS = highly significant ($p < 1\%$)

In this paper we will examine (for surface horizons only):

-the ecological and agronomical factors determining the organic matter content of the soils;

-the nature and characteristics of the organic and organo-mineral compartments of these soils;

-the variations of these compartments for different management practices.

Materials and Methods

Soils. Some characteristics of the main soils studied are presented in table 2. All the cultivated soils from West Africa have been cultivated under traditional systems with low levels of inputs. The sites with minimal influence from erosion or hydromorphy were chosen. None of the soils contained gravel in surface horizons. Soil sampling was done with a corer to a depth of 0-10 cm. Each determination was carried out on a composite sample obtained from 6 to 12 replicates.

Table 2. Climatic and pedological (0-10 cm horizons) characteristics of the main sites studied.

Tableau 2. Caractéristiques climatiques et pédologiques (horizons 0-10 cm) des principales situations étudiées dans ce travail.

n°	Site	Location	Climate		Soil					References
	vegetation*		temp.	pptn.	soil	0-2µm	C	C/N	CEC (pH 7.0)	
			°C	mm	(**)	%	mg g^{-1}		(cmol.kg^{-1})	
1	J,C	Sénégal	29	600	Ft	3	3	10	2	C & N,1971 (1)
2	S,C	Sénégal	29	800	Fl	8	9	15	5	F & M,1977 (2)
3	F,J,C	Togo	27	1040	Fr	9	12	12	5	Poss & al. '84
4	S	Ivory Coast	28	1360	Fl	12	12	16	8	HYPERBAV 1990
	S,J,C	Ivory Coast	28	1360	Fr	19	17	17	12	HYPERBAV 1990
5	Pa,C	Guadeloupe	25	3000	Fr	61	34	10	13	CEE (1988)
6	F,S,C	Martinique	26	1820	Fr	49	44	13	18	CEE (1988)
7	J,C	Sta Lucia	25	2700	Fr	54	30	14	14	CEE (1988)
8	F,C	Brazil	21	1200	Fo	50	36	10	10	Cerri & al '91

(*) Vegetation: F = forest; S = savanna; Pa = artificial meadow; J = fallow; C = continuous cultivation after savanna or forest clearing.

(**) FAO Classification: Ft = cambic arenosol, Fl = ferric lixisol, Fr = ferric acrisol (n° 3, 5) and ferralic cambisol (n° 5, 6, 7), Fo = rhodic ferralsol.

(**) Classification française CPCS: Ft = sol ferrugineux tropical peu lessivé, Fl = sol ferrugineux tropical lessivé à taches et concrétions en profondeur, Fr = sol ferrallitique faiblement désaturé, Fo = sol ferrallitique fortement désaturé (à caractère oxique).

(1) Charreau & Nicou,1971

(2) Feller & Milleville,1977

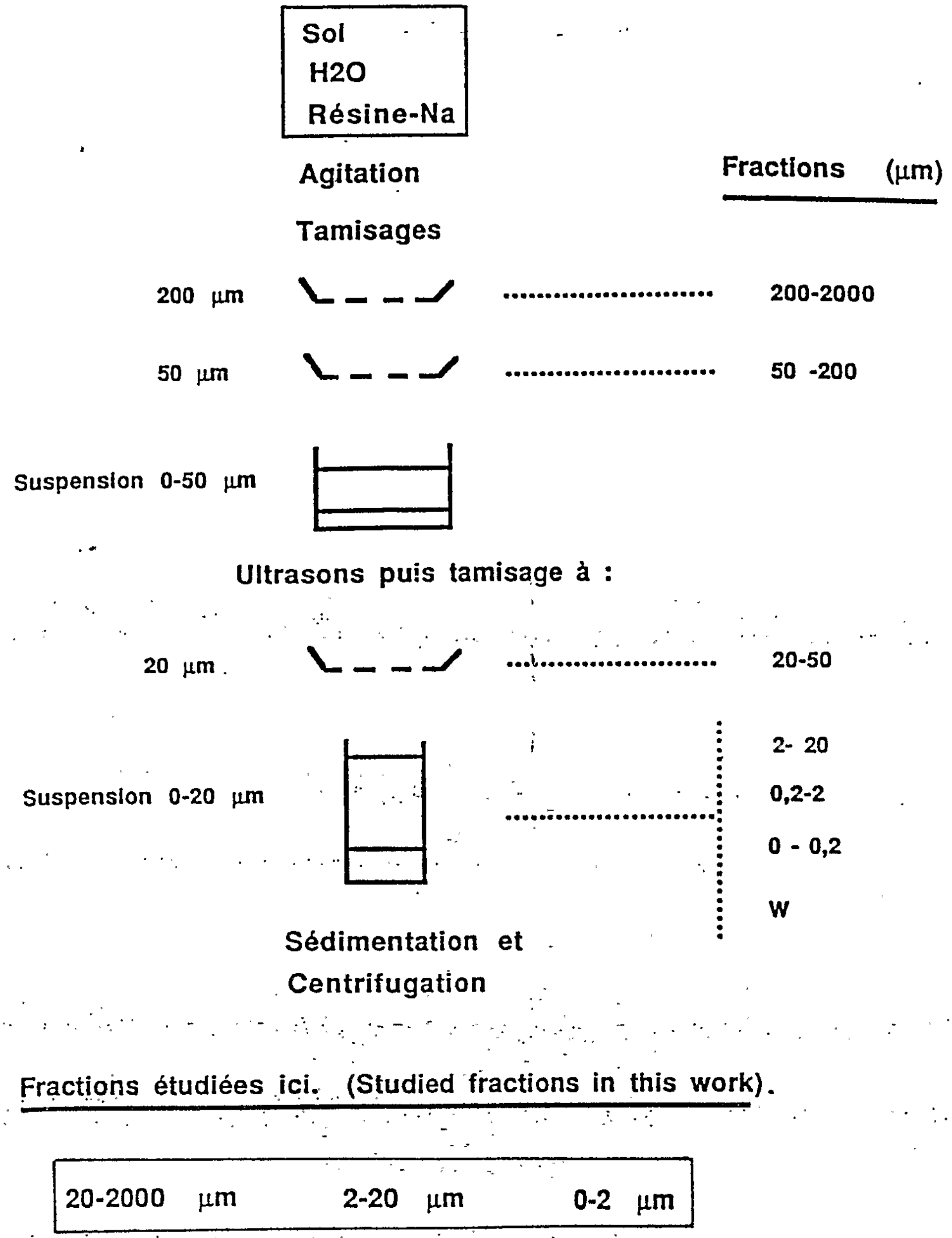

Figure 1. Scheme of the particle-size fractionation of the soil organic matter.
Figure 1. Schéma du fractionnement granulométrique de la matière organique du sol.

Organic matter fractionation (fig. 1). This is a particle-size fractionation (Feller et al., 1991b) on soils previously dispersed with a sodic resin ("Amberlite IRN 77"). 20 to 40 g of soil were shaken for 2 to 16 hours in 300 ml of water with 100 ml of resin. Soils with less than 20% of clay were shaken only for 2 h and 40 g of soil were used. For soils with more than 40% of clay 20 g were used, and the soil was shaken for 16 h. For the other soils (between 20 and 40% of clay) 20 g were shaken from 2 to 6 h depending on their agregate stability. The suspension was then sieved at 200 µm, 50 µm and the 0-50 µm suspension was sonified (to allow a better dispersion of the clay and silt fractions) 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, 0-0.2 µm, and the water used for the fractionation named "W" fraction. In order to simplify the presentation of the results several fractions were combined to give: 20-2000, 2-20 and 0-2 µm. In this study the W fraction contained negligible amounts of C and N.

All analytical determinations were done on samples dried at 50°C until their weight was constant. Total C and N were measured on soils and fractions with a CHN analyser (Carlo Erba model 1106).

Results

Factors determining the organic matter content of surface horizons. Among the climatic parameters which have a direct or indirect influence (through vegetation types) on the level of organic matter in tropical soils, the mean annual temperature (T) and precipitation (P), or their combination (T/P) are considered to be the most important (Jenny et al, 1948; Laudelout et al., 1960; Jones, 1973; Theng et al., 1989). In our sites the average temperature is high and almost constant from 25 to 29°C (except in site 8, 21°C); therefore it is not an important factor in the differentiation of organic matter (Laudelout et al., 1960).

The relation between precipitation (P mm) and the carbon content of the 0-10 cm layers is presented in figure 2a. The coefficient of correlation between these two parameters is low (r^2 =0.38; n = 59) despite a very wide range of precipitation (fig 2a). For instance in the site 4 (Northern Ivory Coast) under similar precipitation levels (1360 mm) the entire range of carbon variation is found within a small watershed.

In addition, there is a very close relation (figure 2b) between carbon and texture (r^2 = 0.801; n =59). This correlation is not significantly improved (r^2=0.805, n=59) by a multiple regression between carbon, soil fines (0-20 µm, $g.100g^{-1}$) and precipitation (P mm). The following equation is then obtained:

$$C(mg.\ g^{-1}soil) = 0.47\ (0\text{-}20\ \mu m\ g,.100g^{-1}) + 0.002\ (P\ mm) - 1.74.$$

This "texture effect" confirms the results obtained by Jones (1973) with a population of 605 savanna soil samples (0-15 cm horizons).

A global "cultivation effect" is shown in the figure 2c. We see that the variation of carbon content depends on soil management practices, and becomes more important when the clay content increases. The decrease of carbon content due to cultivation is equivalent to 30 to 40% of the stock present in the non cultivated soils.

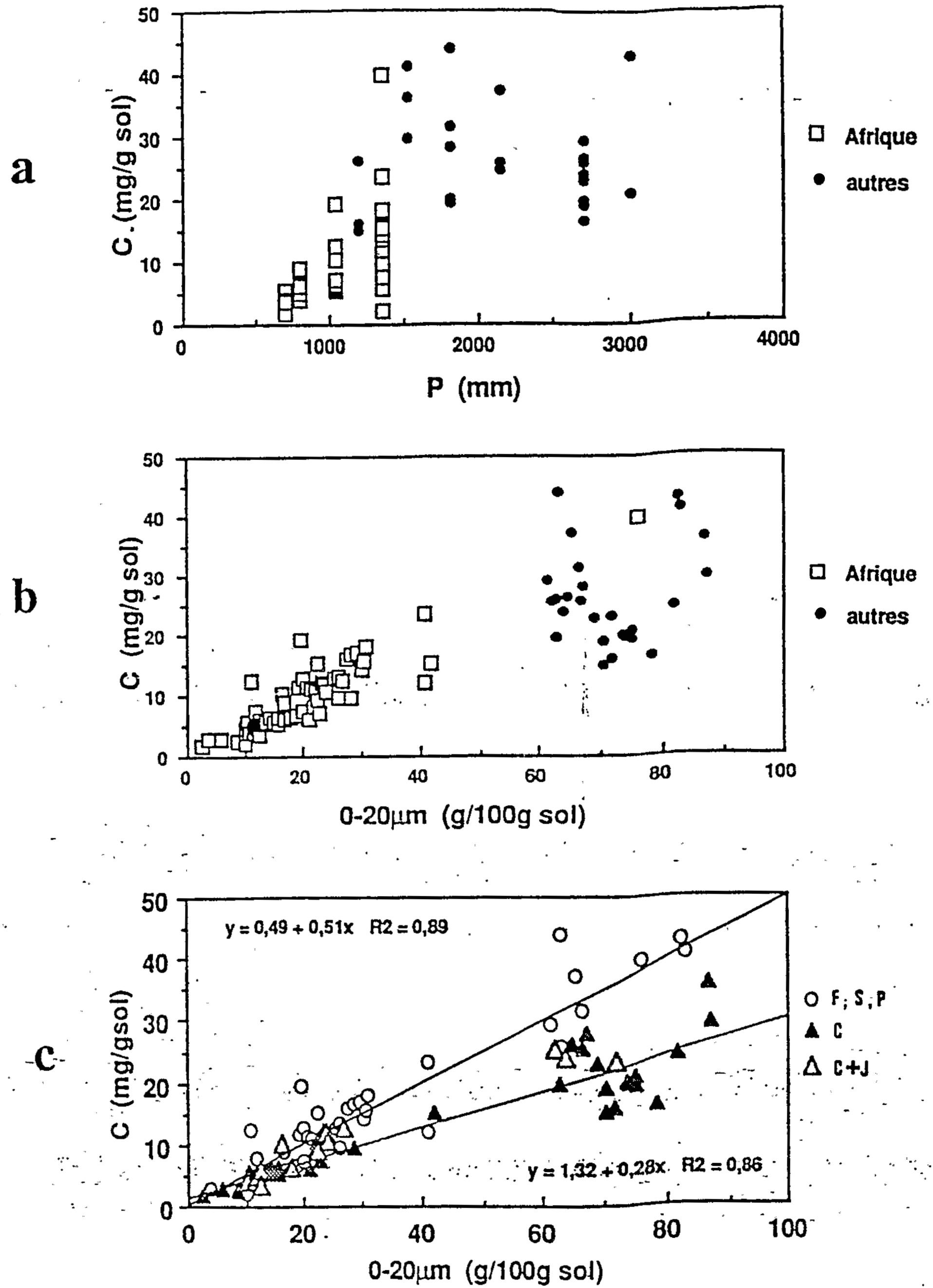

Figure 2. Relationships between carbon content (C), rainfall (P) and texture (0-20 µm). F = forest; S = savanna; P = meadow; C = continuous cultivation; C + J = cultivation-fallow (5 to 10 years) rotation.

Figure 2. Relations entre la teneur en carbone (C), la pluviométrie (P) et la texture (0-20 µm). F= forêt; S = savane; P = prairie; C = culture continue; C + J = rotation culture-jachère (5 à 10 ans).

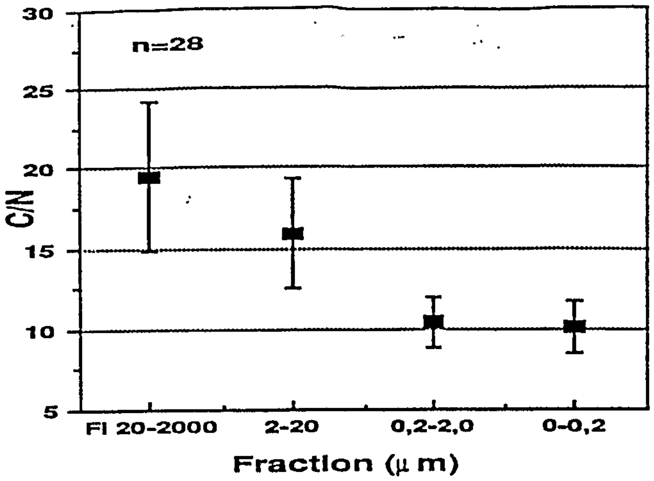

Figure 3. Mean values and standard deviations of the C/N ratio of the different particle-size fractions (West African sites).
Figure 3. Moyennes et écart-types des rapports C/N des différentes fractions granulométriques (situations d'Afrique de l'Ouest).

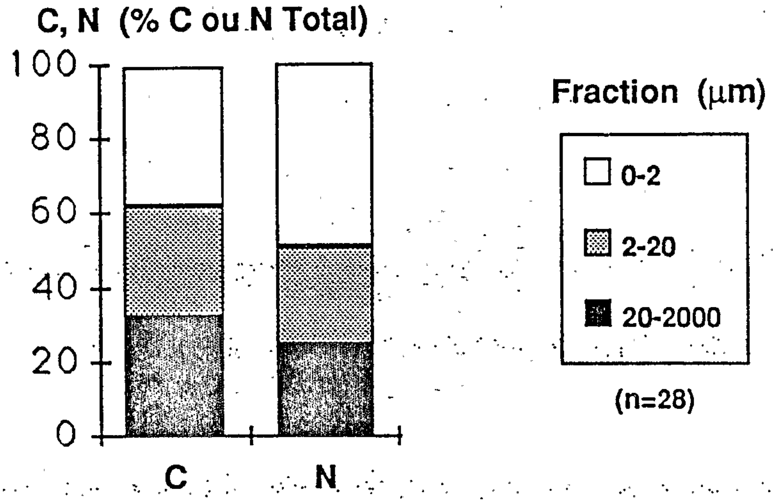

Figure 4. Carbon (C) and nitrogen (N) distribution between particle-size fractions of the soil (West African sites)
Figure 4. Répartition du carbone (C) et de l'azote (N) dans les différentes fractions granulométriques (situations d'Afrique de l'Ouest).

Soil organic matter characterisation. Observations at different scales (binocular lens, optical and electronic microscopy) of organic matter associated with particle-size fractions of low activity clay soils (Feller, 1979; Feller et al., 1991c) allow the separation of soil organic matter into three particle-size fractions on a morphological basis:

fraction 20-2000 µm: plant debris variably decomposed and associated with sand and coarse mineral silt.

fraction 2-20 µm: mostly plant and fungal debris associated with fine mineral silt and very stable organo-silt microaggregates not dispersed during the fractionation procedure.

fraction 0-2 µm: predominantly of organo-mineral microaggregates containing amorphous organic matter sometimes associated with plants or fungal parietal debris. Presence of some bacteria either isolated or in colonies. Amorphous organic matter is predominant in this fraction.

The average C/N ratios of the fractions obtained on 28 different samples from West Africa are 20, 16, 10 and 10 for the fractions 20-2000, 2-20 0.2-2 and 0-0.2 µm respectively (figure 3). The average C/N ratios are not significantly different between 20-2000 and 2-20 µm but they are different between 2-20 and the 0.2-2.0 and 0-0.2 µm. The high values found in the fractions greater than 2µm (C/N > 15) agree with the observation of plant debris in these fractions. The average distribution of carbon and nitrogen (as a percentage of total C and N) is presented for the same samples in figure 4. The plant debris (20-2000 µm) contains 30% of the total C and 25% of nitrogen, the fine silt 30% of C and 30% of N, and the clay 40% of C and 50% of N.

Variations of the different organic and organo-mineral fractions in relation to the texture. The comparison of three sites (2, 4 and 8) under natural vegetation (SA, and F) shows that the carbon content of the different fractions varies according to the texture (figures 5a1, b1, c1):
-the carbon content of the 20-2000 µm fraction is almost constant and does not depend on the texture (3 to 5 mgC.g^{-1} soil);
-the carbon content of the 2-20 µm fraction increases slightly with the texture (3 to 8 mg C. g^{-1}soil);
-in the 0-2 µm fraction, carbon increases strongly with the texture (3 to 17 mg C. g^{-1}soil).

These variations are similar for comparable cultivated situations (C9, C10, C12). The high organic matter content of the clayey soils are then essentially due to an important organic matter storage in the clay fraction and to a lesser extent in the silt. These variations with texture observed for tropical soils are similar to those observed in cold or temperate regions (see Tiessen and Stewart, 1983; Balesdent et al., 1991 for instance).

Variations of the different organic fractions with soil management practices. Two types of situations are considered:
-situations with decreasing organic matter content: clearing-cultivation succession
-reclamation of degraded soils: cultivation-fallow (or seeded pasture) succession.

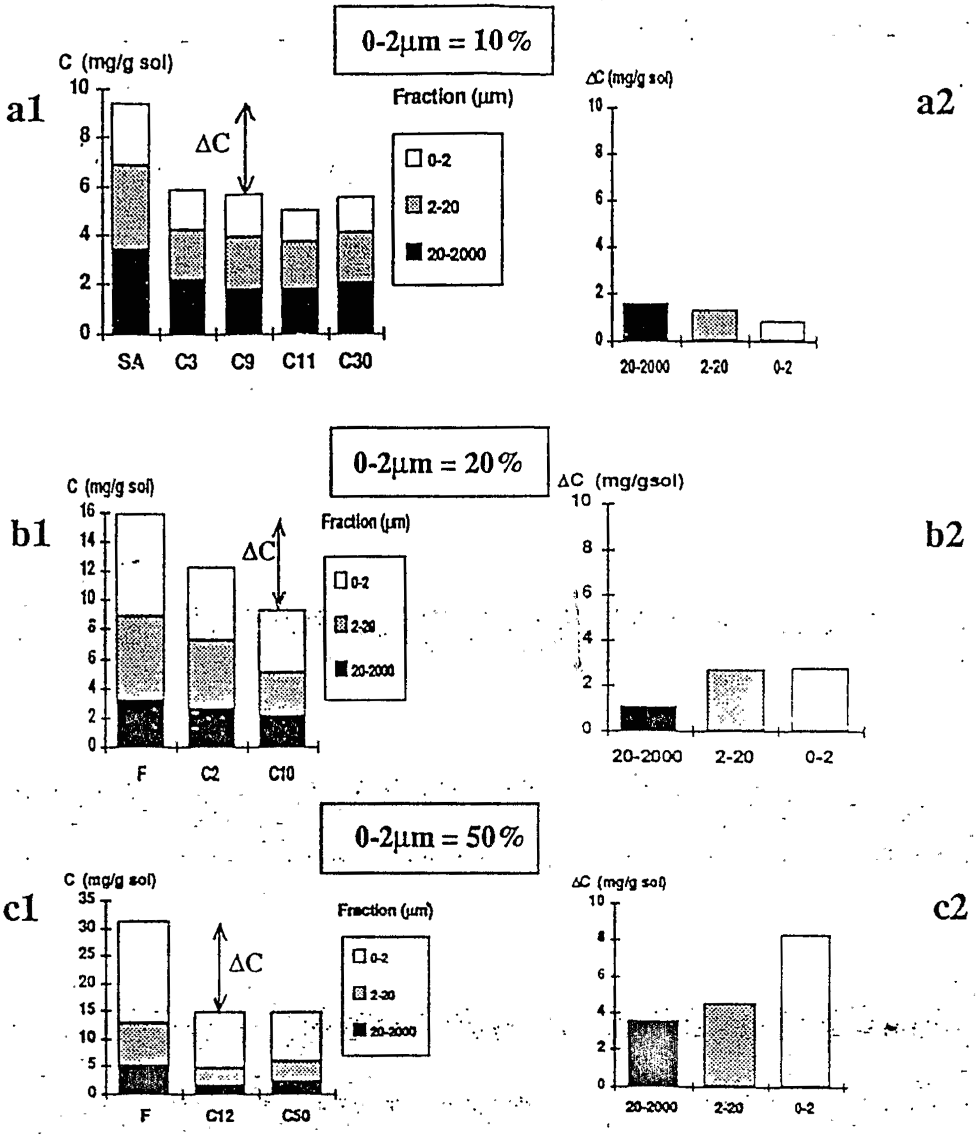

Figure 5. Effect of cultivation after clearing on the carbon contents of the soils and different particle-size fractions. DC (mg $C.g^{-1}$ soil) represents respectively the difference between the sites SA and C9 (Fig. 5a1 and 5a2), F and C10 (Fig. 5b1, 5b2) and F and C12 (Fig. 5c1, 5c2). Abreviations: F = forest, SA = tree savanna, C(3) = cultivation (3 years). The Fig. 5a, 5b, and 5c are respectively related to sites 2, 4 and 8.

Figure 5. Effet de la mise en culture après défrichement sur les teneurs en carbone (mg $C.g^{-1}$ sol) des sols et des différentes fractions granulométriques. DC (mg $C.g^{-1}$ sol) représente les différences entre les situations SA et C9 (Fig. 5a1 et 5a2), F et C10 (Fig. 5b1, 5b2) et F et C12 (Fig. 5c1, 5c2). F = forêt, SA = savane arborée, C(3) = culture (3 ans). Les Fig. 5a, 5b, et 5c correspondent respectivement aux situations 2, 4 et 8.

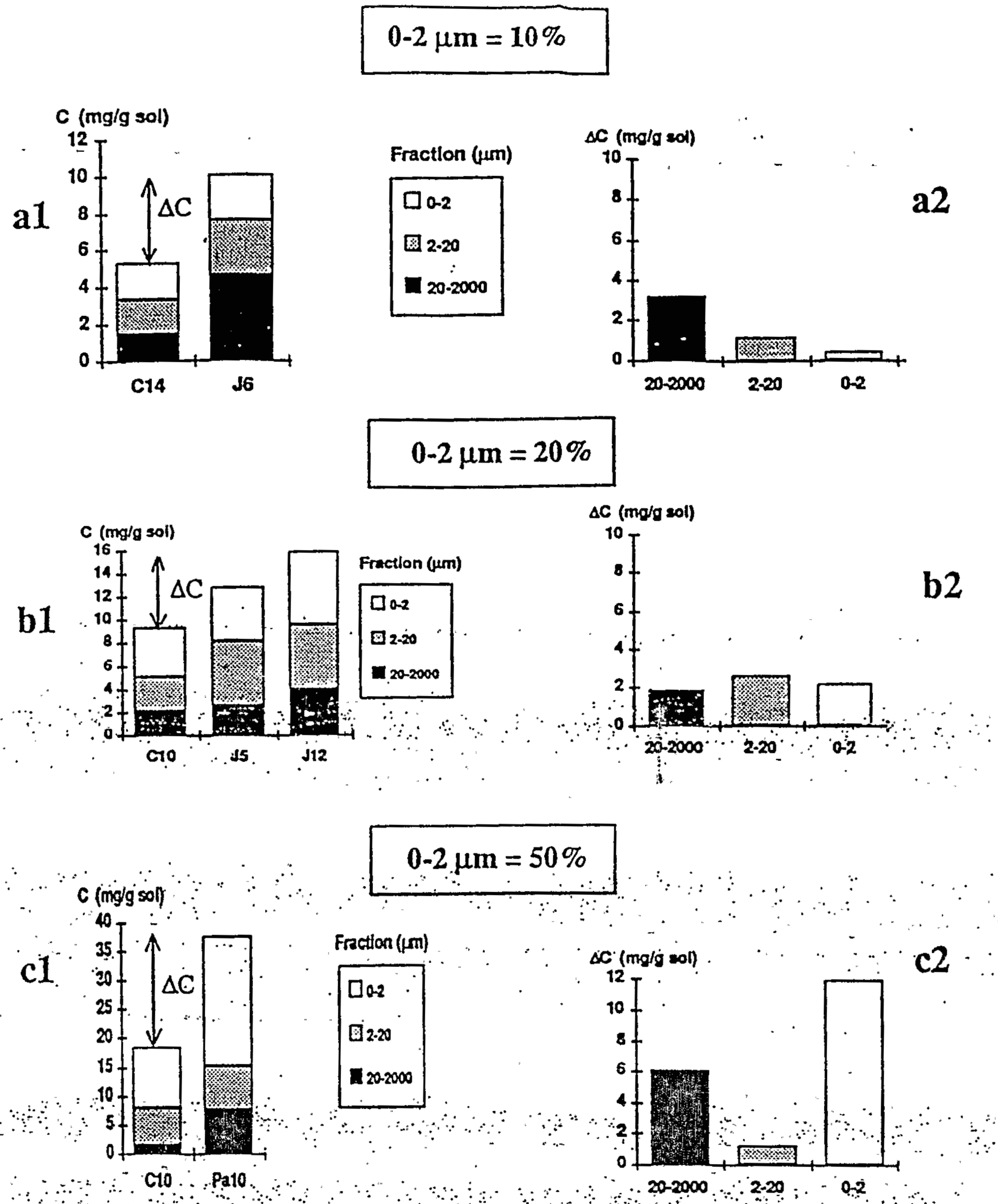

Figure 6. Effect of fallows or meadow after continuous cultivation on the carbon contents of the soil (mg C.g^{-1} soil) and different particle-size fractions. DC (mg C.g^{-1} soil) represents respectively the differences between J6 and C14 (Fig. 6a1 and a2), J12 and C10 (Fig. 6b1, and b2) and Pa10 and C10 (Fig. 6c1, and c2). Abreviations: Pa = artificial meadow, C(10) = cultivation (10 years). The Fig. 6a, 6b, and 6c are respectively related to sites 3, 4 and 5.

Figure 6 : Effet de la mise en jachère ou prairie, après cultures continues sur les teneurs en carbone (mg C.g^{-1} sol) des sols et des différentes fractions granulométriques. DC (mg C.g^{-1} sol) représente les différences entre les situations J6 et C14 (Fig. 6a1 et a2), J12 et C10 (Fig. 6b1, et b2) et Pa10 et C10 (Fig. 6c1, et c2). Abreviations: Pa = prairie artificielle, C(10) = culture (10 ans). Les Fig. 6a, 6b, et 6c correspondent respectivement aux situations 3, 4 et 5.

a) Clearing-cultivation succession. Three situations with varying clay contents are considered: 10 g.100g^{-1} (site n°2), 20 g.100g^{-1} (site n°4), 50 g.100g^{-1} (site n°8). The decrease of total carbon (figure 5a1, b1, c1) due to cultivation becomes more important with increasing clay content. This agrees with the variations observed in figure 2. Note also that the decrease is faster in the sandy soils (3 years) than in the clayey soils (10 years) (compare figures 5a1 and b1).

The differences in behaviour of the fractions depend also on soil texture. In the sandy soil (figure 5a2) the decrease (DC) is mostly due to the 20-2000 µm fraction (plant debris) and secondarily to the 2-20 µm fraction. On the contrary, in the clayey soils (figure 5c2), the decrease is mostly due to organic matter associated to the 0-2 µm fraction. The sandy-clayey soil has an intermediate behaviour between the sandy and the clayey soil.

b) Cultivation-fallow (or pasture) succession. Three situations with varying clay content (figure 6) are studied: 10 g.100g^{-1} (site n°3), 20 g.100g^{-1} (site n°4), 50 g.100g^{-1} (site n°5). The carbon content increases when the soils are fallowed or brought to pasture (figures 6a1, b1 c1). This increase becomes more important with increasing clay content. This agrees with the variations observed in the figure 2c.

The behaviour of the different fractions varies also with soil texture. In the sandy soil (figure 6a2) the increase (DC) is essentially caused by the 20-2000 µm fraction (plant debris) and to a lesser extent by the 2-20 µm fraction. In the clayey soil under pasture the increase is mostly due to the 0-2µm fraction and secondarily to the 20-2000 µm fraction (plant debris). The carbon content of the silt fraction does not vary much. The sandy-clayey soil has an intermediate behaviour between the sandy and the clayey soils (figure 6b2).

Discussion and conclusions.

The organic matter content of well-drained low activity clay soils under a warm climate (T > 20°C) studied here depends essentially on soil texture for a range of precipitation between 600 to 3000 mm. The climate (precipitation and temperature, duration of the dry season) had a lesser effect. Therefore local variations (in a watershed) or even site variations (in a field) of the texture will have a similar effect on organic matter content in the surface horizons than regional variations (on the scale of West Africa for instance). This "texture effect" concerns both the cultivated and non cultivated situations. Cultivation leads to a loss of 30 to 40% of the initial organic stocks.

The particle size fractionation of organic matter, based on the separation of organic matter associated to sand, silt and clay, appears to be well adapted to the study of the influence of soil texture on the storage and dynamics of organic matter. Moreover, it is clear from previous work done in temperate or tropical situations (Turchenek and Oades, 1979; Feller, 1979; Anderson et al., 1981; Tiessen and Stewart, 1983; Feller et al., 1991b for instance) that organic matter associated with sand is mostly in the form of plant debris, whereas organic matter associated to clay is much more amorphous. Depending on the soil type and on the stability of clay-silt-organic matter associations, the organic matter associated with fine silt is more or less similar to one of the two fractions (>20 µm or <2 µm). Thus simple particle size fractionations allow to separate very different organic compartments.

In sandy soils with low carbon content, the amounts of organic matter associated with 20-2000, 2-20 and 0-2 µm are almost equal. Over several (> 10) years the variations of organic stocks are mainly due to fractions >2 µm and to a lesser extent to fractions <2 µm (fig 5a2 and 6a2). Similarly Martin et al.(1990) found, with a $\partial^{13}C$ technique applied to low activity clay soils under native vegetation in Lamto (Ivory Coast), that in 16 years, 90 to 100% of the organic matter associated with fractions >50 µm turned over, but only 40 to 50% for fractions <50 µm.

On the contrary, in clayey soils, higher in organic matter, 60 to 70% of the organic matter is associated with the clay fraction, and the role of this fraction becomes dominant in long-term variations of the organic matter budgets (figure 5a3, and 6a3). The sandy-clayey soils have an intermediate behaviour between these two extremes.

Most of the surface horizons of the low activity clay soils of West Africa have a sandy to sandy clayey texture (clay < $25g.100g^{-1}$). Therefore, in these soils, the plant debris (20-2000 µm) will have a great importance in biogeochemical processes. An illustration of this has been given by Blondel (1971) for sandy soils from Sénégal. This author showed the importance of "free organic matter" on a seasonal scale, in the mineralization of soil nitrogen. A recent study (Feller and Nicolardot, unpublished) confirms these results for the fractions >2 µm in the situations studied here.

The conservation of soil properties and fertility requires proper management of soil organic matter. However, with the increase of populations in the semi-arid sahelo-sudanian zone and the present agricultural practices, the possibility of organic matter returns to soils are reduced since long term fallow is not practiced any more, and straw or stubble that could be restituted to soils are used for other purposes (building, fuel, animal feed). A lot of research is still needed to find agricultural practices able to increase organic matter returns to soil: crop rotations, based on crops with strong root systems, short term fallows, agroforestry systems or association of agriculture and animal husbandry (Pieri, 1989).

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