The Status of Soil Organic Matter in Selected Fragile Ecosystems

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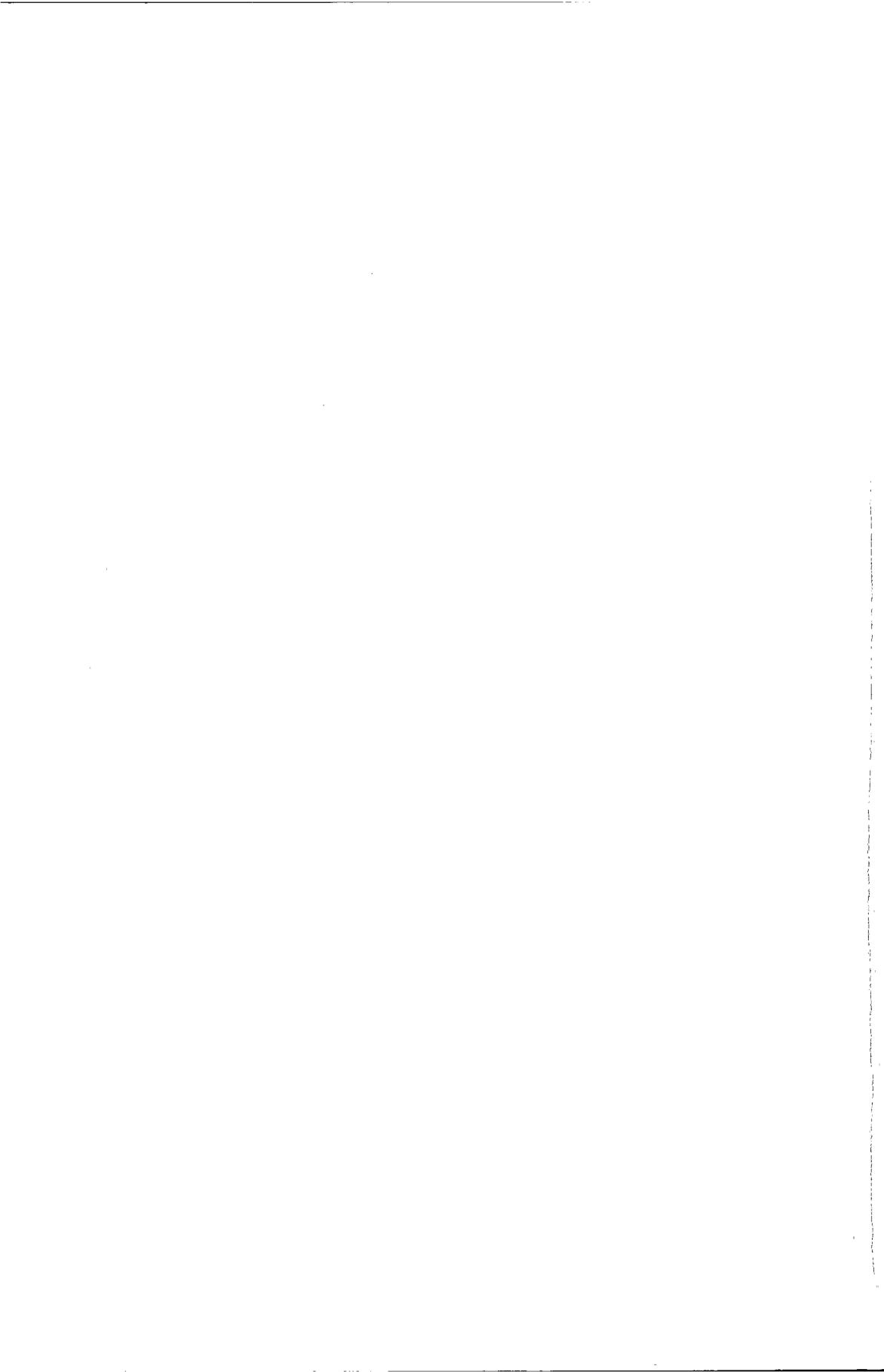[b]Université d'Orléans, Laboratoire de Géochimie Organique, URA 724, BP 6759 45067 Orléans Cédex, France

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Abstract
     The amounts and composition of soil organic matter (SOM) are regulated by long-standing equilibria between inputs and outputs. Climatic changes, which have progressively modified these equilibria in the past, affect different regions at the present time. In pre-sahelian or sudanese-sahelian Africa, negative effects appeared to be the combined result of low SOM and clay contents, and of inadequate farming or grazing. In the Amazon basin, severe effects of anthropic deforestation and pasture installation on soil fertility and SOM characteristics were recorded. This paper aims at a better knowledge of SOM contents ang origins, in terms of carbon (C) and nitrogen (N) contents, grain-size fractionation of humic substances (HS), and separation into fulvic acids (FA), humic acids (HA), and humin. The proportions of C derived from forest and pasture in SOM and HS fractions were determined by $\delta^{13}C$ measurements.

1. INTRODUCTION

     It is well established that the amount sand composition of soil organic matter (SOM) accumulated in the successive soil layers depend on the equilibria between *inputs* (from litterfall, decaying organisms, and fertilizers), and *outputs* (through mineralization, leaching and cropping). As a whole, *fragile ecosystems* can be defined as those in which external changes, especially climatic or anthropogenic ones, modify these equilibria, with far reaching consequences on soil characteristics, including in most cases, soil humus.
     Changes in external factors generally result in the installation of a different vegetation cover, inducing subsequent changes in both quantity and quality of SOM, especially humic substances (HS). For a given soil type, the main factor

responsible for SOM accumulation is generally the *climate*. Under steady climatic conditions, another important factor is *soil drainage*, which determines changes in water content at seasonal, and even daily scale. As a third factor, *human activity* is to be considered, especially in third world tropical areas, which are affected by rapid changes in land use, in relation with demographic developments.

The present paper is divided into two main parts. The first one resumes basic information regarding SOM turnover, and its changes due to natural, mainly climatic, changes. In the second part, the impacts of anthropic factors are presented, and examples taken from the african and south-american tropics are emphasized. The importance of SOM as an index of soil fertility and biological activity are discussed, and the need for further research about the chemical structure and properties of HS in tropical soils is stressed.

2. THE IMPACTS OF NATURAL CHANGES ON SOM

2.1. Local climate history

For a given soil type, the main factor responsible for SOM accumulation is frequently the *climate*. The effect of climatic changes during the Quaternary on SOM amounts and quality was shown by Guillet {1} in the case of french podzols. Figure 1 shows that increasing SOM contents are caused by colder and wetter climates, resulting in increasing apparent ages, or in other terms, in decreasing turnover rates.
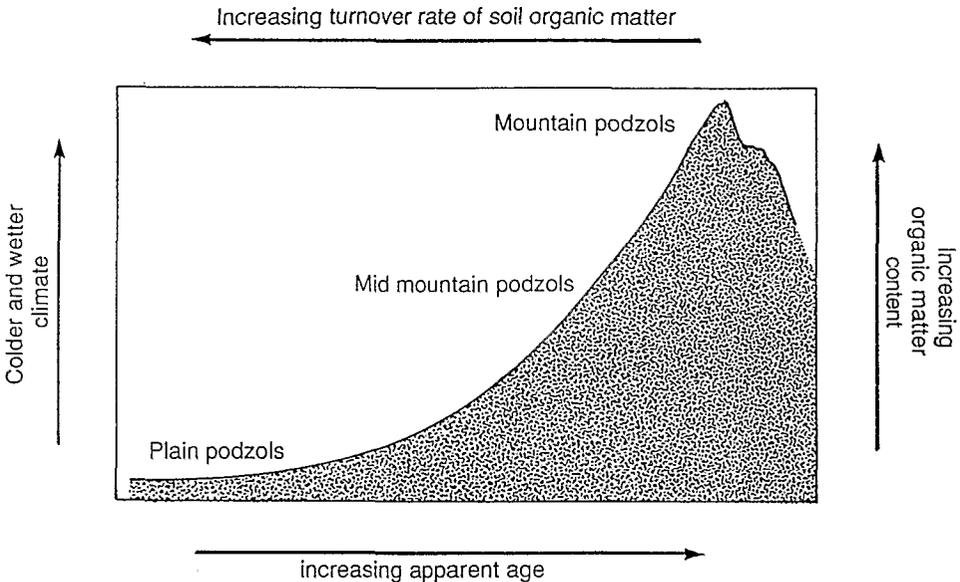
Figure 1.   Effects of general climate on soil organic matter turnover in Bh horizons of forest podzols. Adapted from Guillet {1}.

As all the studied horizons were podzol Bh, it was interesting to relate their apparent age to the estimated duration of podzolisation in the referred areas. Using palynological information, this author proved that podzolisation was exclusively present between the Subboreal and Subatlantic periods, *i. e.* that in all cases, podzolisation started about 4,500 years BP. Figure 2 shows that the ^{14}C apparent age of SOM (between about 200 and 1,200 years) was much lower than the duration of podzolisation, probably due to an active turnover rate. These values appeared to be young, in contrast with those published by Scharpenseel *et al.* (2) who obtained values from 1,680 up to 3,000 years in the deeper layers of nine selected podzols.
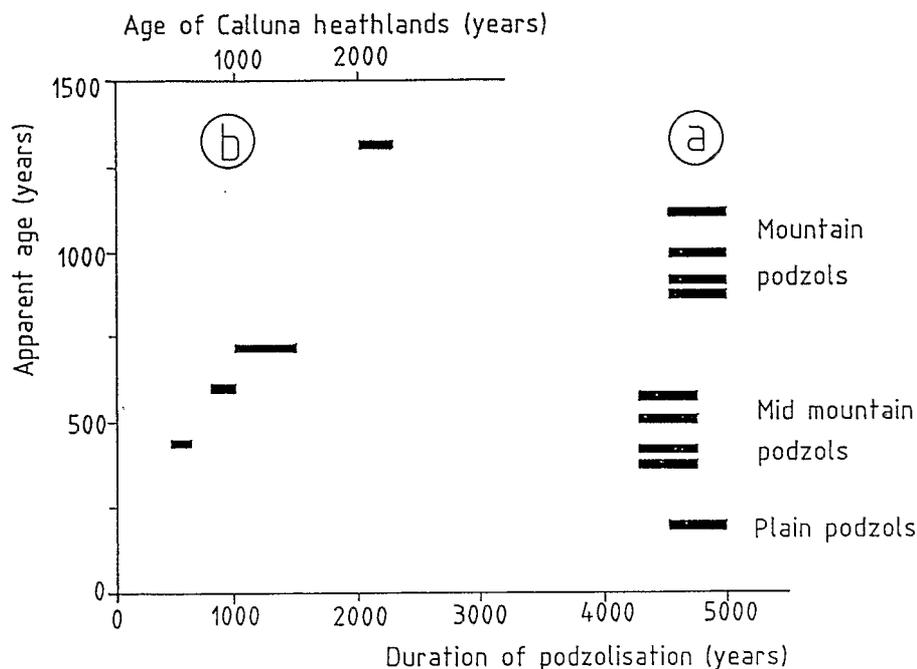

Figure 2. Apparent age of Bh horizons as a function of the duration of podzolization in forest podzols (a), and the age of *Calluna* heathland in degradation podzols (b). After Guillet {1}.

The apparent age of SOM in Bh horizons from forest podzols increased with increasing altitude, and almost no relationship with the duration of podzolisation was observed. Contrarily, in degraded podzols developed under *Calluna* heathlands, the apparent age of SOM increased linearly with the age of the substitution of the hardwood forest by the *Calluna* vegetation. In fact, it is possible that in some cases, Bh horizons pre-existed before the vegetation change, but there is no doubt that the *Calluna* cover was responsible for an

increased production of low turnover rate HS, which contributed to enhance the morphological differentiation of the Bh horizons.

Regarding the distribution of fulvic acids (FA) and humic acids (HA), Table 1, which summarizes results from fourteen podzols of the Vosges mountain (France) shows that the forest podzols on sandstone had much lower humus contents in their Bh horizons, than other podzols. All of them had high proportions of extractable HS, and presented variable FA/HA ratio. The main difference was that the podzols on crystalline (granite) parent rocks exhibited much higher relative proportions of FA than the former ones on sandstone. This difference has not been explained so far.

Table 1
Distribution range of humic fractions from podzol Bh horizons derived from different parent rocks and vegetations.

	Soil	Humin	FA	HA	FA/HA
		(mg/g C of Soil)			
Forest podzols on sandstone (4)	7.0 - 15.0	2.5 - 6.6	2.1 - 6.8	2.1 - 3.7	1.0 - 1.8
Heathland podzols on sandstone (5)	22.0 - 54.0	6.3 - 18.4	8.7 - 24.0	6.4 - 22.6	0.6 - 1.7
Forested podzols on granite (5)	23.0 - 56.0	6.0 - 13.0	14.1 - 28.0	1.6 - 8.5	3.2 - 10.5

Numbers of sites appear in parentheses. Adapted from Guillet {1}.

2.2. Changes in soil water content

Whithin a given climatic area, the distribution of HS fractions can be modified by seasonal changes, resulting in different SOM patterns, according to the duration of the wet period. In their study about podzols of south-west France, Righi and Wilbert {3}, showed that a lesser accumulation of SOM occured in drained podzols, than in those of wet heathlands. In drier conditions, organic rests were decomposed with lower production of HS in the soil surface. Contrarily, less root material was developed in the hard Bh iron pan of the drained podzols than in the loose Bh horizons of the wetland podzols, resulting in a larger proportion of extractable material in the former than in the latter.

A similar comparison was carried out by Faivre et al. {4} in tropical podzols of the Magdalena valley in Colombia. These are deep podzols, with low amounts of organic C in the A horizons. The drained podzols often contained larger amounts of organic C than the hydromorphic ones, including in the B horizons. As in the temperate podzols, larger proportions of unextractable HS accumulated in the A horizons of the drained podzols. The same pattern was observed in the B horizons of the drained podzol, which containted larger

amounts of unextractable HS than those of the hydromorphic podzols, contrary to what happened in the temperate podzols.

Dry conditions do favour the polymerization of small into larger humic molecules, as clearly observed by Ferry {5} who established a negative correlation between the FA/HA ratio and the duration of the dry season in different tropical soils from India (Figure 3). Losses of FA and small size HA, through either solubilization under wet conditions, or fast mineralization under dry conditions, seemed to result in a decrease in SOM content, following a parabolic regression curve. This confirmed earlier observations by Turenne {6} who showed that the percentage of non mobile HA in soils from the French Guyana was maximum at the beginning and lower at the end of the humid season.
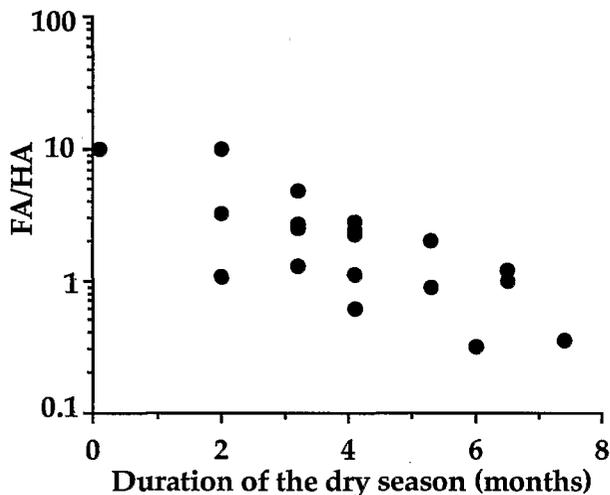

Figure 3. Relationship between the duration of the dry season and the FA/HA ratio of the 0-2 µm fraction, in surface soils from the Western Ghâts region, India, sampled at the end of the rainy season. After Ferry {5}.

3. IMPACTS OF HUMAN ACTIVITY ON SOM IN THE TROPICS.

Little has been done so far about the formation, transformation and translocation processes of HS in tropical soils, although most of developing countries having urgent need for solutions to their agricultural problems are located in tropical areas. Changes in carbon cycling that can occur in soils due to the introduction of new, sometimes inadequate agricultural practices, has been investigated by comparing natural carbon-isotope depth distribution in these soils {7-9}. The following examples, which were taken preferentially from

the dry and humid tropics, suggest that SOM content and quality can be critical parameters that control soil properties and fertility in these areas.

3.1. Annual crops in pre-sahelian areas of Africa

In pre-sahelian or sudanese-sahelian areas, the uneven distribution of rains, especially the existence of two very contrasted seasons, affects the adequation of yields of traditional agriculture to the increasing population needs. Together with possible medium-term climatic changes, this increases the risks of desertification. As far as the effect of traditional agriculture on total SOM content is concerned, a curve of the type shown on Figure 4 is obtained. It can be observed that the content of SOM derived from the initial savanna vegetation has decreased about four times in 180 years of cultivation, following a linear decay equation during about 30 years, then an exponential equation, with an annual decay coefficient of about 2‰, till a plateau was reached near a C content of 0.58 %.

The decay varies according to soil type, climate, and obviously, land use : by plotting SOM content *versus* that of fine mineral (*i.e.* clay + silt) colloids, Pieri {10} has proposed a critical index of SOM content for the conservation of soil agricultural properties. Although such a relationship is very inexplicite, especially for low clay contents, it gives an idea of the minimal SOM required to avoid high risks of soil physical degradation.
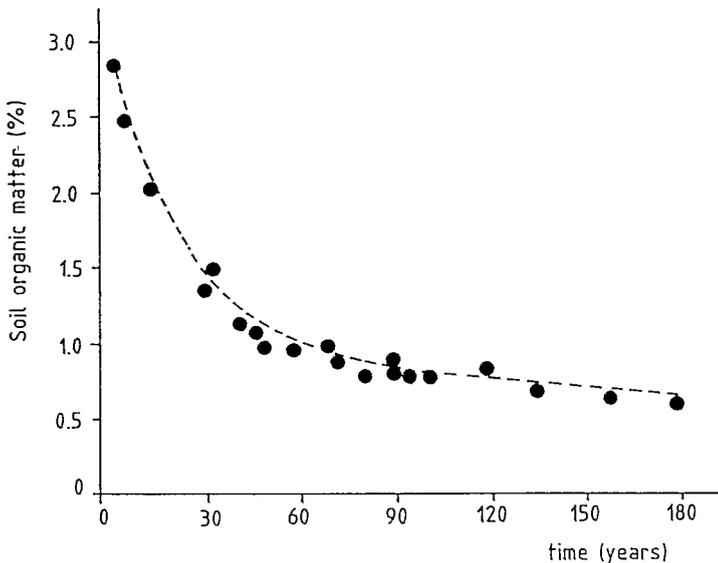

Figure 4. Relationship between organic matter content and time elapsed since deforestation in cultivated soils from Casamance, Senegal. After Siband {11}.

Organic matter has been recently studied by Dutartre *et al.* {12} in cultivated luvisols of two sequences from Mali and Burkina Faso. In the study areas, the pluviosity was about 1 m yr^{-1}, with two very contrasted seasons. As shown on Figure 5, these soils, especially those from Mali, had relatively low organic C and N contents (C/N ratios varied from 13.5 to 18.2) and low proportion (30-50%) of extractable HS. They exhibited from 44.6 to 69.1% of hydrolyzable material, in which carbohydrates predominated. The soils from Mali yielded larger proportions of hydrolyzable N, especially amino acids, than those from Burkina Faso.
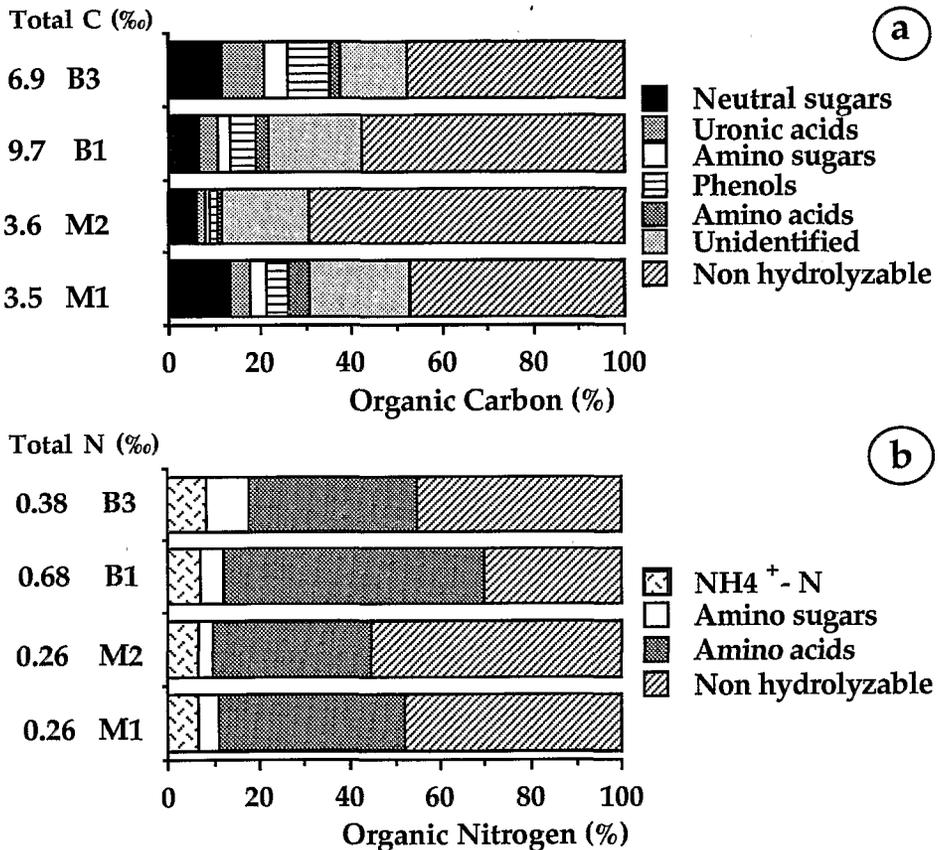

Figure 5. Distribution of carbon (a) and nitrogen (b) forms in two toposequences from Burkina Faso (B1 and B3) and Mali (M1 and M2). B1 and M1 were in upper position ; B3 and M2 were in lower position. After Dutartre *et al.* {12}.

Among carbohydrates, the predominant role of uronic acids and osamines, rather than that of neutral sugars, was established. Attention was placed on uronic acids, the proportion of which was related to total C content and

aggregate stability. The relationship between aggregate stability and SOM content was surveyed. In Figure 6, WSA 1h refers to the proportion of water-stable aggregates with a size higher than 200 µm, which were retained on a brass sieve after one hour of gentle shaking {13}. It can be observed that this index of aggregate stability was mainly correlated with organic C content, with highly satisfactory regression coefficients. The location of the study samples on the regression curve clearly shows that the soils from Burkina Faso were much more stable than those from Mali (about 10% of WSA against 5%, respectively).
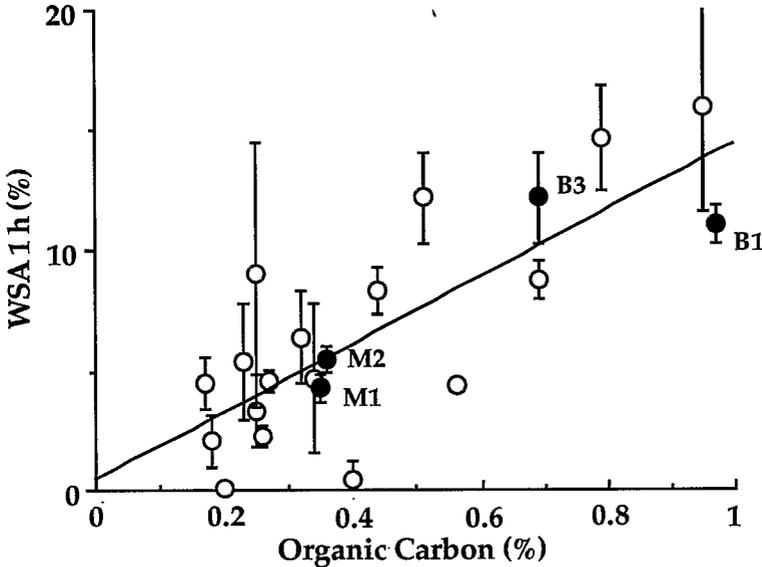

Figure 6. . Relationship between water-stable aggregates (WSA 1h) and soil organic matter content of top soil. • samples M1, M2 (Mali), B1, B3 (Burkina Faso) selected for organic matter analysis. After Dutartre et al. {12}.

3.2. Annual crops in eastern Amazonia

Most of the examples presented below are taken from the Capitão Poço area in the State of Pará, in eastern Amazonia, and from the north Manaus area, in central Amazonia. In these areas, agricultural practices imply slashing of the native forest, removal of the economically interesting species, and generally burning of remaining trees and bushes, at the end of the dry season. In eastern Amazonia, the changes in SOM content and composition have been studied in an experimental area of shifting agriculture {14, 15}.

As already stated in earlier papers {14-16}, total C content of the upper soil layer first decreased in all cases, due to the burning of above ground residues. After one year cropping, only a slight increase in the relative proportion of FA was noticed. However, with increasing cropping time, the yields were decreasing, and the total amount of C decreased. Furthermore, after five years,

a strong increase in the proportion of extractable HS, mainly FA, occured. This was correlated with a decrease in soil structure and porosity, and an increase in soil bulk density. Thereafter, when the soil was left fallow for a number of years, it was observed that it tended to recover its initial characteristics. Nevertheless, only the total amount of organic C was recovered, but the newly formed SOM was mainly concentrated in the coarse fraction, with no recovery of its initial binding to fine silt and clay-size colloids. Table 2 indicates that in the study area, the soil was very sensitive to losses of SOM bound to fine mineral fractions through surface erosion, once the area was deforested and cultivated. Similar observation was also reported in the case of Cocoa tree-planted soils of central-south Cameroon {17}.

Table 2
Distribution of organic carbon and nitrogen in the fine silt and clay fractions of cultivated and fallow soils, as compared with native forest soils.

| | Size fractions (μm) | | | | | | | |
| | 0 - 0.2 | | | | 0.2 - 5 | | | |
	weight %	C mg/g	N	C/N	weight %	C mg/g	N	C/N
Forest								
0-10 cm	3.7	205.3	21.2	9.7	52.8	82.1	6.3	13.0
Cocoa rubber								
0-10 cm	2.8	136.7	15.0	9.1	58.5	60.5	5.2	11.6
Pennisetum								
0-10 cm	1.4	125.6	11.0	11.4	47.7	44.1	4.0	11.0
Fallow 6 years								
0-10 cm	1.1	112.8	9.1	12.4	21.0	59.4	5.5	10.8
Fallow 8 years								
0-10 cm	1.2	91.5	6.5	14.1	29.6	42.2	3.3	12.8

Adapted from Pavani *et al.* {18}.

3.3. Cultivated pastures in the Amazon basin

The distribution of HA, FA, and humin in the profile of a feralsol, following slash-and-burn and cultivation for 10 years of a *Pennisetum purpureum* pasture was studied (Figure 7). This method did not show any significant difference between the initial and deforested sites, except a slight tendency toward a higher proportion of humin in the upper layers of the pasture soil. The distribution of organic C derived from forest and from pasture in these three humus fractions of the pasture soil was determined, based on their differences in $\delta^{13}C$ values {19}. It is now well known that recent changes of vegetation or cultivation from C3 to C4 plants result in increasing $\delta^{13}C$ values in the topsoil, when compared to the uncultivated forest soil {8,20}. In some cases however, an increase in $\delta^{13}C$ with depth can occur, as a result of vertical translocation of material and metabolites from the new plant cover {8}. In the present case, such translocation processes were suspected, based on

morphological features, but not clearly evidenced by the $\delta^{13}C$ distribution. Figure 7 indicates that the proportion of C derived from pasture in HS was low, especially in the HA fraction. This proportion was higher in the humin fraction in the two surface layers, and higher in the FA fractions in the deeper layer.
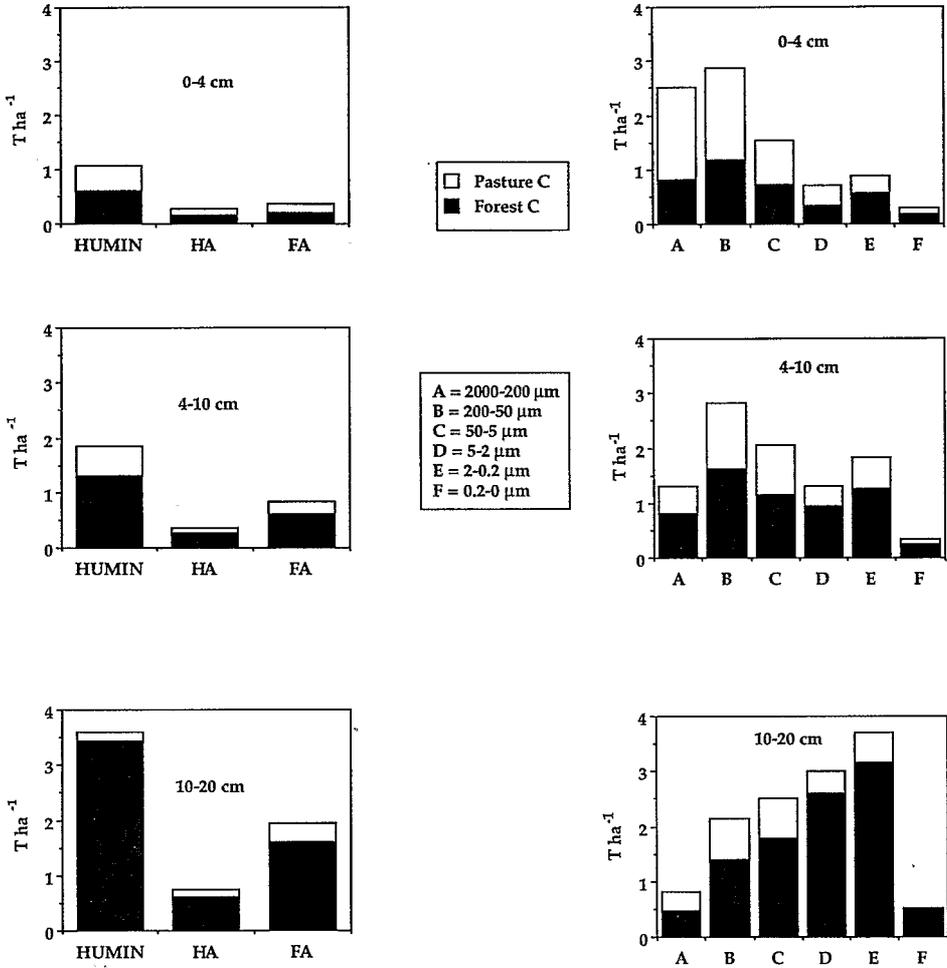

Figure 7. Distribution of carbon derived from forest and from pasture of *Pennisetum purpureum*, after ten years of pasture installation, in chemical fractions (left) and grain-size fractions (right) of three upper layers of a yellow feralsol from Eastern Amazonia. After Desjardins {19}.

In order to determine which fractions concentrated organic C derived from pasture, δ^{13}C measurements were carried out on the size fractions of the pasture soil. Figure 7 also indicates that most of the material derived from pasture was in the coarse fractions, especially in the upper soil layers. Some influence of the pasture was still noticed at 20 cm depth, probably due to root decomposition, but almost no C derived from pasture could be detected in the deeper soil layers. Similar results were obtained in different areas of the Basin [21-23].

In general, the proportion of C derived from pasture was influenced by local climatic conditions, as well as by soil characteristics. In eastern Amazonia, the probably worse conditions were encountered, due to the very short dry season, as well as to the sandy texture of these soils. On the contrary, in central Amazonia [21], and furthermore in south-western Amazonia [24], more contrasted climate conditions favoured a higher incorporation of C derived from pasture within the fine fractions.

4. RELATIONS BETWEEN CHANGES IN SOM CONTENT AND C/N RATIO

Different parameters can be chosen to determine the possible changes in the biological activity of a soil horizon. One of the simplest ones is based on the determination of the C/N ratio, which is related to the intensity of protein biosynthesis : the higher the biological humification, the lower the C/N ratio [25].
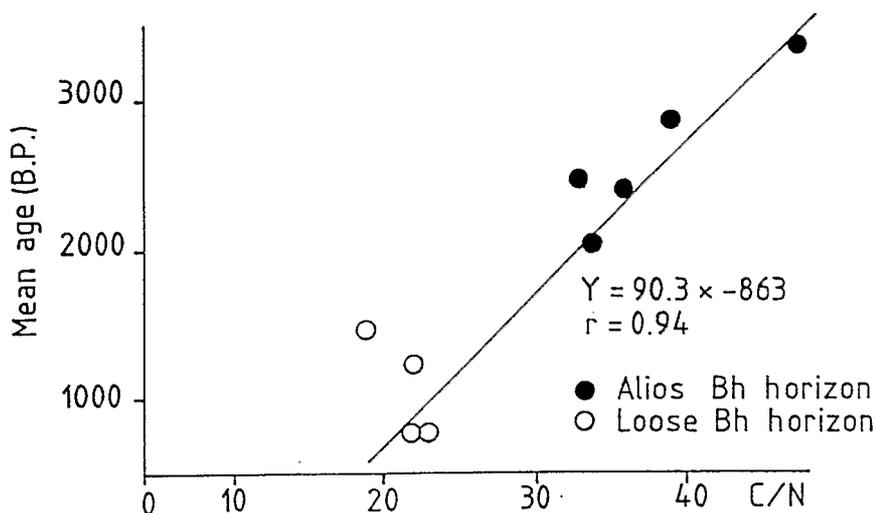

Figure 8. Relationship between C/N ratio and ^{14}C mean age of spodic horizons in a sequence of podzols at Lagunan, South-West France. After Righi and Guillet [26].

Again in the case of the spodic horizons, Righi and Guillet {26} showed that the C/N ratio was directly related to the ^{14}C mean age of SOM. The data shown on Figure 8 are from a toposequence where the oldest podzols presented a hard iron pan, whereas the youngest ones were loose and formed by micro-aggregates of biological origin. This was illustrated experimentally, by incubating spodic horizons differing in their mean ages, and studying the daily amounts of CO_2 evolved. As a matter of fact, the younger podzols were more active, and their SOM more biodegradable.

In general, it is well known that the C/N ratio of the fractions decreases with their decreasing size, as reported by numerous authors {27-29}. A relationship was also observed between C/N ratios and $\delta^{13}C$ values in different instances. In their study of a North-German podzol , Bertram and Schleser {30} reported that the variations of C/N ratios along the profile coincided with those of $\delta^{13}C$ values. Moreover, they observed that in the B_{hs} horizon, a strong $\delta^{13}C$ decrease was accompanied by an increase in the C/N ratio. They attributed this feature to a selective decomposition and removal of organic fractions richer in N and [13]C.
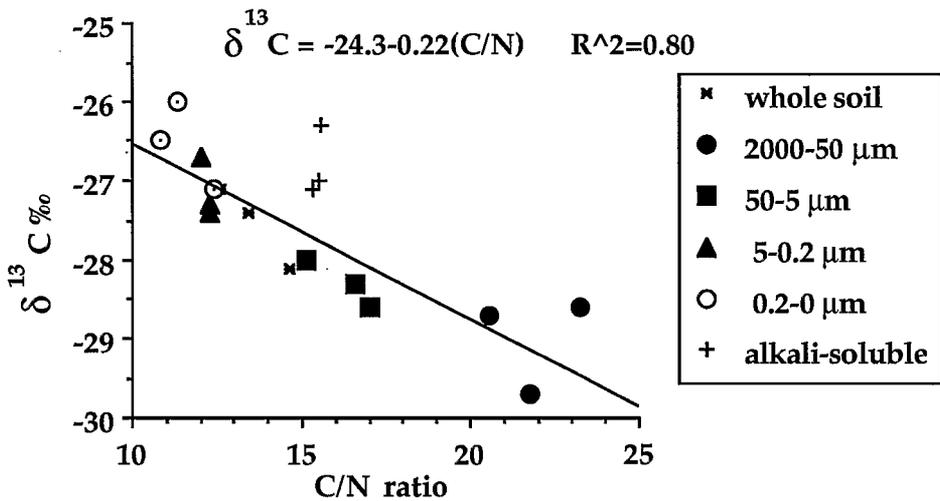

Figure 9. Relationship between $\delta^{13}C$ values and C/N ratios in grain-size fractions of upper layers of a feralsol from central Amazonia (regression curve does not include whole soils and alkali-soluble fractions). After Choné et al. (unpublished data)

In an Amazonian forest soil, a similar relationship was observed whithin the size-fractions of three successive upper layers of a rain forest soil. Figure 9 shows that the $\delta^{13}C$ values increased with both decreasing C/N ratios and decreasing size. Humus fine fractions possibly contained two categories of N

forms : (i) a first one, which predominated, and was probably the result of intense microbial activity, inducing ^{13}C discrimination {31}, and (ii) a second one, which was less abundant and almost completely derived from the pre-existing organic compounds. Actually, scientists are still argueing about the possible effect of humification processes on ^{13}C isotope fractionation. It can be observed here that the extractable HS of the three layers had intermediate C/N values, which were close to that of the whole soil, whereas their $\delta^{13}C$ values were outside the regression curve, and close to the $\delta^{13}C$ values of the two clay-size fractions.

5. DISCUSSION AND CONCLUSIONS

This review has attempted to illustrate the relationships between the changes in soil organic matter content and quality, and the fragility of the ecosystems. When natural ecosystems are in equilibrium, soil organic matter is considered as the result of slow transformation processes under steady or smoothly variating climatic conditions. However, when sudden changes in soil organic matter and its transformation processes occur, they may result from either strong natural (mainly climatic) changes, or from anthropogenic changes, or both.

Quantitative changes have been reported, especially in relation with the changes in vegetation cover and humus organic sources. Some detailed studies about the impacts of agricultural practices on interdependent humus composition and soil aggregate stability, are now available. However, strong changes in soil organic matter quality can probably occur ; humic substances are frequently modified and degraded as a result of these changes, but in most cases, almost no information is available in terms of fine humus chemistry. Although modern characterization techniques have been applied to soil organic matter of agricultural situations in temperate areas, less is known about its qualitative changes in tropical soils, especially in developing countries. There is a pressing need for a better knowledge of the structure of humic substances in these environments, and the mechanisms of their transformations.

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