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Carbon content in a yellow Latosol of central Amazon rain forest [1]

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ABSTRACT

In a distrophic yellow heavy clay Latosol of Central Amazon rain forest, Manaus district, the equivalent of 3.6 tC/ha is immobilized as litter, 9.6 tC/ha as roots and 230 tC/ha are stored as humus in the soil. Humus is found up to 5 m deep in the profile. Only 1/3 of the humic carbon is in extractable form (humic and fulvic acids); the remaining part is in the form of humin.

KEY-WORDS: *Soil - Carbon - Rain forest - Brazil.*

RÉSUMÉ

Dans un Latosol jaune, distrophe et très argileux de la forêt d'Amazonie centrale, région de Manaus, 3,6 tonnes de carbone par hectare sont immobilisées dans la litière, 9,6 tC/ha se trouvent sous forme de racines et 230 tC/ha sont stockées dans le sol sous forme d'humus. Dans le profil on rencontre de l'humus jusqu'à 5 m de profondeur. Seulement un tiers du carbone de cet humus est extractible sous forme d'acides fulviques et humiques; le reste est représenté par de l'humine.

MOTS-CLÉS : *Sol - Carbone - Pluviisylve - Brésil.*

1. — INTRODUCTION

In forests, carbon is immobilized in the form of different organic compounds in living and dead plants, in animals and microorganisms and also in the soil as humus.

Although the carbon content in biomass is frequently evaluated by ecologists, little is known about the total quantity of carbon stored in the soil. Soil organic matter is often determined but the results cannot be used to calculate the total quantity, on an areal basis, because they are invariably expressed as percentages and lack the values for bulk density (SCHLESINGER, 1977). In addition these results do not lead to a complete quantitative evaluation because frequently only the upper layers of the soil profile are sampled. Even under tropical conditions the amount of organic matter in the deeper layers is not negligible (VOLKOFF & CERRI, 1981).

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This research was carried out in the Amazon region to determine the total amount of soil carbon in a representative forest soil. It represented the first step of a large program whose goal was the study of the carbon cycle and its changes within the Amazonian basin.

The place chosen for this work was the Reserve area of the Instituto Nacional da Amazonia, known as Bacia Modelo, near Manaus, where several other ecological studies are being carried out. This area is at km 60 of the Manaus-Boa Vista highway. Soils are uniform yellow latosols (Brazilian system of classification) or Haplorthox (U. S. Soil Taxonomy) developed from sedimentary material. They are deep, well drained, very acid clays (BRASIL, 1976; BRASIL, 1979; CHAUVEL, 1981).

The vegetation is a dense Amazon high forest. The climate is characterized by an annual average precipitation of 2,100 mm, with a minimum value between July and September, and a mean annual temperature of 26.7° C.

2. — MATERIAL AND METHODS

2.1. *Local characteristics and general methods of soil analysis*

Field work was carried out in April 1982, almost at the end of the rainy season.

The profile studied was located on the top of a plain topography with a very smooth convex declination (1 %), in a primary forest area. A morphological description of the profile was made in a 3 m deep trench especially opened for the study (fig. 1). Layers 10 cm thick were sampled inside the pedological horizons, and the following analyses were made: particle size analysis with pyrophosphate and ultra sounds dispersion, carbon (C), and nitrogen (N) by dry combustion (C, H, N, S,

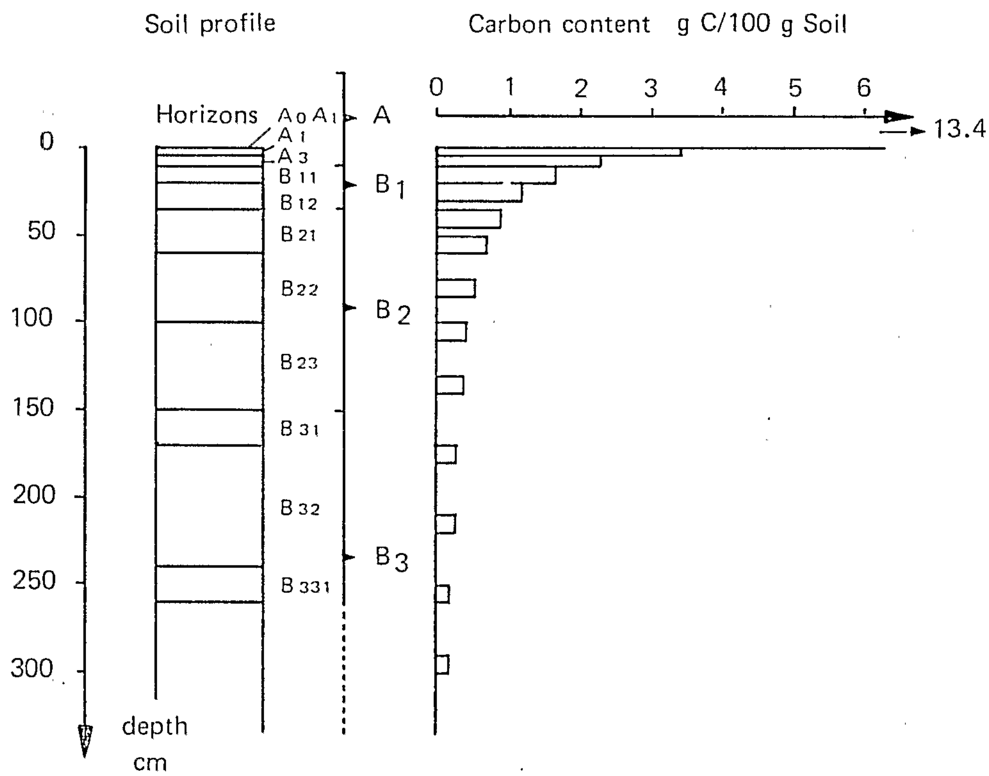

FIG. 1. — Schematic profile of the soil studied and carbon contents in the layers analysed.

Carlo Erba), sum of exchangeable cations (S) on an ammonium acetate extract at pH 7, cation exchange capacity (*CEC*) with calcium chloride, exchangeable aluminium (Al^{3+}) and hydrogen (H^+) in a normal sodium chloride solution extract. Some X-ray and differential thermal analysis (*DTA*) determinations were also made with whole soil and with the clay fraction.

2.2. *Litter and soil carbon determination*

The litter was sampled at 3 different places, approximately 50 m apart. A 1 m^2 area was isolated with a wooden frame and all the material in the frame was collected. Sampling for soil carbon (0-4 cm) was made in the same three 1 m^2 plots. The 0-4 cm layers were completely removed by scraping with a knife and weighed. Carbon analysis was made on a composite sample.

Sampling below 4 cm was made at one place only. Cylindrical holes of approximately 10 cm diameter and 10 cm deep, were dug up with five replications at each depth interval within 1 m^2.

The total soil from each cylinder was kept in sealed plastic bags. The sample volume was measured by calibrated dry sand. After sampling each layer, the 1 m^2 pit was deepened to the next layer to be sampled. The space between layers increased in depth, but never exceeded 30 cm.

The number of replications varied with depth. Four replications were made for each layer down to 1 m. At depths beyond 1 m three replications were made for each layer. The last layer sampled was 290-300 cm.

All coarse roots in the 1 m^2 were collected. Every soil bag was separately weighed. After being weighed, all the material from the same layer was mixed and air-dried.

Coarse plant fragments (essentially roots) in the air-dried soil were separated using a 2 mm sieve, weighed and dried at 60° C in an oven and ground. Similarly in litter, constituents were air-dried, weighed and dried at 60° C. Carbon analysis was made on a ground, dried (60° C) sub-sample.

Soil carbon was quantified in a sub-sample of ground air-dried soil. A sub-sample of the air-dried soil was dried at 105° C for the bulk density calculation.

Carbon was analyzed by dry combustion in a Carbon Biological Oxidizer apparatus.

Total carbon in a 30 cm deep soil column was calculated directly, as all layers had been sampled. From 30 cm down a graphic interpolation was made between the layers analyzed.

The humus was characterized by the Dabin (1971) method for all samples collected up to 1 m deep. Using this method we determined the distribution of soil organic carbon in the soil humic fractions: free fulvic acids extracted with phosphoric acid; fulvic and humic acids extracted with alkaline sodium pyrophosphate and sodium hydroxide solutions; humins (the organic fractions that cannot be extracted by these acid and alkaline solutions). A low density (light organic residues) fraction removed during the phosphoric acid treatment was separated by filtration.

3. — RESULTS

3.1. Pedological characterization of the soil

3.1.1. *Morphology*

The litter layer was 10 cm thick, and consisted of a continuous layer of dried leaves, with a few dried branches. A thin layer of partly decomposed fragments, brown and black, not exceeding 2 cm thick, was found in direct contact with the soil.

The profile (fig. 1) shows the following horizons:

A0/A1 0-1 cm: Dark grey. Clay. Moderate medium granular structure. Many fine and very fine pores. Many fine roots. Clear smooth boundary.

A1 1-4 cm: Grey (10 YR 5/4) moist. Clay. Weak coarse granular structure. Very friable. Common fine and very fine tubular pores. Few fine roots. Gradual smooth boundary.

A3 4-10 cm: Light grey (10 YR 5.5/4) moist. Clay. Massive structure. Very friable. Common very fine tubular pores. Few fine roots. Diffuse smooth boundary.

B11 10-20 cm: Yellowish grey (10 YR 6/4) moist. Clay. Massive structure. Friable. Common very fine tubular pores. Few fine roots. Diffuse smooth boundary.

B12 20-35 cm: Yellow (10 YR 6/6) moist. Clay. Massive structure. Friable. Common very fine tubular pores. Few roots. Diffuse transition.

B21 35-60 cm: Yellow (10 YR 7/6) moist. Clay. Massive structure. Many very fine tubular pores. Few fine roots. Diffuse smooth boundary.

B22 60-100 cm: Yellow (10 YR 7/8) moist. Characteristics similar to above, a little more friable.

B23 100-150 cm : Yellow (10 YR 7/7) moist. A little less porous and less friable. Weak fine angular blocky structure.

B31 150-170 cm : Yellow (10 YR 7/6) moist. Characteristics similar to above.

B32 170-240 cm : Yellow (10 YR 7/6) moist. Few medium diffuse red mottles. Massive structure. Friable. Many very fine tubular pores. Diffuse smooth boundary.

B331 240-260 cm : Yellow (10 YR 7/5) moist. Less porous.

B332 260-300 cm : Light yellow (2.5 YR 7/4) moist. The structure becomes weak fine angular blocky.

3.1.2. *Physical, chemical and mineralogical characteristics*

This soil has a very high clay content, it is strongly distrophic and has a small amount of total iron (table I) which is in accordance with results concerning yellow latosols of the Manaus region (BRASIL, 1979; CHAUVEL, 1982).

Characteristics such as carbon distribution in the soil profile are also generally in accordance with what has been found in Manaus (VOLKOFF *et al.*, 1982).

X-ray and DTA analyses show that the soil material is composed of quartz, kaolinite, and small amounts of gibbsite (fig. 2). No significant mineralogical variation is observed in the successive profile layers.

In the Manaus region all the pedological studies were made to a depth of 2 m and there is no information about B3 horizons of yellow latosols. It is thus unknown whether the characteristics found for this single profile studied, *i. e.*, decrease in porosity, increase in cohesion, increase of pH to 6, incipient mottles, are properties common to Manaus yellow clay latosols.

We suggest that the soil selected is representative of yellow latosols north of Manaus, at least in the 0-150 cm of the profile. It seems that it was imperfectly drained at greater depths, but there is no information as to whether this is linked to the chosen site or whether it is a general characteristic of the deep horizons of the yellow latosols of this region.

3.2. QUANTIFICATION OF CARBON LITTER

At the end of the rainy season there was an average of 1,000 g of dry matter/m^2 of litter on the soil (table II). This is equivalent to 360 gC/m^2. Approximately 63 % of this amount consisted of entire dry leaves; the balance is divided between branches and decomposed leaves.

According to KLINGE *et al.* (1975), in the yellow latosols of the Amazon forest an annual deposit of dry matter as litter is equivalent to 1,000-1,200 g/m^2. The dry weight corresponds therefore to the annual litter fall.

TABLE I. — *Analytical characteristics of the soil (Fe_2O_3, total Fe_2O_3).*

Depth	Clay	fine silt	C	N	pH		EXCHANGEABLE CATIONS						CEC	Fe_2O_3
							Ca	Mg	K	Na	Al	H		
cm	%		%		H_2O	KCl	me/100 g						me/100g	%
1- 4	78	5	34.0	2.8	4.1	3.7	0.15	0.15	0.11	0.07	2.18	0.47	12.0	3.0
4- 10	76	9	23.1	2.0	4.3	3.9	0.06	0.03	0.05	0.04	1.95	0.31	9.0	3.3
10- 20			16.7	1.5	4.6	4.1	0.06	0.03	0.03	0.03	1.56	0.31	8.0	2.9
35- 45	77	17	8.8	1.0	5.2	4.3	0.06	0.01	0.01	0.02	2.03	0.23	5.0	3.3
75- 85			5.4	0.4	5.4	4.2	0.06	0.01	0.01	0.01	1.01	2.23	2.4	3.3
130-140	65	27	4.0	0.3	5.4	4.2	0.06	0.01	0.01	0.01	0.78	0.16	2.0	3.8
210-220			2.8	0.3	6.6	4.5	0.06	0.01	0.01	0.02	0.47	0.16	2.0	2.6
250-300	85	11	2.1	0.2	6.3	4.5	0.06	0.01	0.01	0.02	0.48	0.00	2.0	2.6

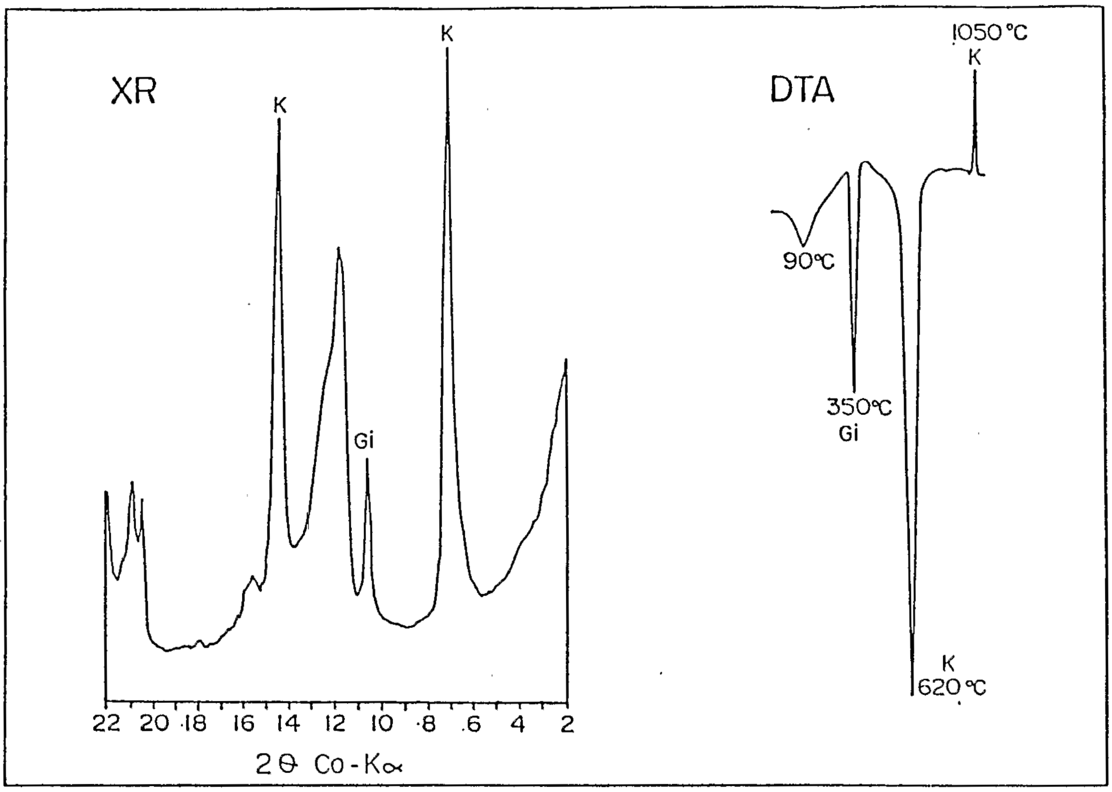

FIG. 2. — X-Ray diffraction (*XR*) and differential thermal analysis (*DTA*) curves of a soil sample of the 290-300 cm layer (*XR*, powder in clay fraction; *DTA* in total soil; *Gi*, gibbsite; *K*, kaolinite).

TABLE II. — *Dry matter and total carbon content in litter fraction.*

litter fraction	dry matter (60°C)		total carbon	
	mass	Carbon content		
	g/m^2	%	gC/m^2	relative %
leaves	610	37.09	226	63
branches	219	36.17	79	22
decomposed leaves	185	28.55	53	15
total	1014		358	100

3.3. SOIL CARBON MASS

Two fractions were separated: one < 2 mm, which is the fine earth containing humic substances and small organic fragments (light organic residues), and another > 2 mm which consists only of plant fragments.

3.3.1. *Carbon < 2 mm fraction*

Total carbon concentration of this fraction decreased rapidly within the 0-35 cm layer (table III); after which it stabilized and decreased slowly. At 3 m depth carbon concentration was at least 1.8 mgC/g.

Figure 3 shows the C distribution in the profile. At depths greater than about 200 cm the decline in carbon becomes linear. The yellow latosols of the central Amazon basin, developed on soft sedimentary material, are often 10 to 20 m thick (IRION, 1984), and their topmost 8 m are composed of the same homogeneous clayey horizons. It seems unlikely that any sudden change in carbon content occurs in this interval of depth. For these reasons we might predict that the decline remains linear (or becomes more marked) below 3 m.

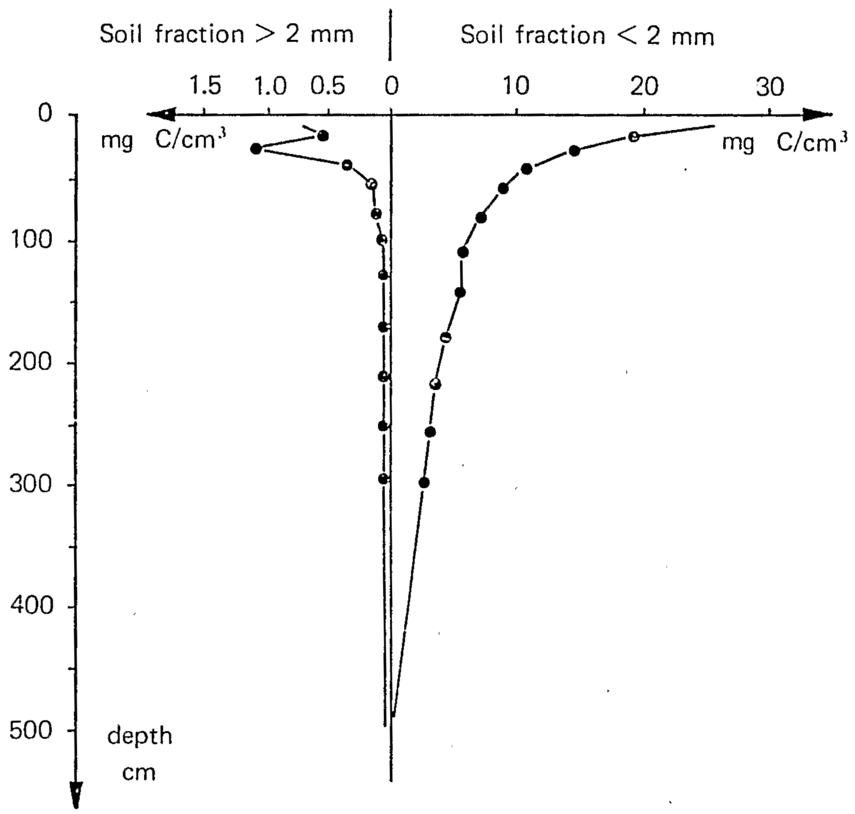

FIG. 3. — Variation in carbon content with depth in soil fractions (< 2 mm and > 2 mm).

On the basis of a linear decline we estimate that, at 5 m depth, the carbon concentration should be nil and, according to this, it is possible to calculate the maximum total carbon in a soil column. The 1 m^2 soil column contained 22,958 gC/m^2 or 230 tC/ha (table IV). The cumulative quantities of carbon in the < 2 mm fraction increased gradually with depth, and the 0-100 cm portion of the profile contained only 50 % of the carbon of the fine earth fraction (fig. 4).

The carbon value obtained in this soil is greater than that found in the literature. For example, for tropical soils SCHLESINGER (1977) indicated a mean of 104 tC/ha,

TABLE III. — *Carbon content of the analyzed layers* (d1, *105° C dried soil weight/volume*; d2, *air dried soil weight/volume*).

Depth cm	d1	d2	Soil fraction <2 mm		Soil fraction >2 mm
			mgC/g air dried soil	mgC/cm^3 soil in situ	mgC/cm^3 soil in situ
0- 1	+	+	133.6	*	*
1- 4	+	+	34.0	*	*
4- 10	1.097	1.119	23.1	26.06	0.715
10- 20	1.102	1.137	16.7	18.99	0.501
20- 30	1.165	1.196	12.1	14.47	1.155
35- 45	1.156	1.185	8.8	10.51	0.308
50- 60	1.167	1.194	7.2	8.94	0.140
74- 84	1.222	1.244	5.4	7.00	0.113
100-110	1.271	1.296	4.5	5.83	0.042
130-140	1.424	1.453	4.0	5.81	0.034
170-180	1.416	1.441	3.2	4.61	0.026
210-220	1.299	1.326	2.8	3.71	0.033
250-280	1.549	1.583	2.0	3.17	0.016
290-300	1.539	1.566	1.8	2.82	0.032

+ not determined
* Carbon of these layers was calculated by m^2 because the total layer was collected.

TABLE IV. — *Cumulative carbon mass with increasing depth.*

Depth cm	Carbon in <2 mm fraction		Carbon in >2 mm fraction		Total fraction	
	of layer	Cumulative	of layer	Cumulative	of layer	Cumulative
			g/m^2			
0- 1	233	233	18.6	18.6	251.6	251.6
1- 4	815	1048	312.0*	330.6	1127.0	1378.6
4- 10	1564	2612	42.9	373.5	1606.9	2985.5
10- 20	1899	4511	50.1	423.6	1949.1	4934.6
20- 30	1447	5958	115.5	539.1	1562.5	6497.1
30- 40	1182	7140	53.9	593.0	1235.9	7733.0
40- 55	1459	8599	33.6	626.6	1492.6	9225.6
55- 80	1992	10591	31.6	658.2	2023.6	11249.2
80- 95	1604	12195	19.4	677.6	1623.4	12872.6
95-135	1746	13941	11.4	689.0	1757.4	1463.0
135-175	2084	16025	12.2	701.2	2096.2	16726.2
175-215	1660	17685	10.8	712.0	1670.8	18397.0
215-500	5273	22958	77.0	789.0	5350.0	23747.0

* including 230.1 due to presence of coarse roots.

and AJTAY *et al.* (1979) reported 75 to 145 tC/ha. For the entire upper 2 m of a yellow ferrallitic soil of the tropical forest of Cameroon, HUMBEL *et al.* (1977) calculated 120-180 tC/ha. For soils of the Manaus region KLINGE *et al.* (1975) obtained 145 tC/ha and CHAUVEL (1982) 122 tC/ha.

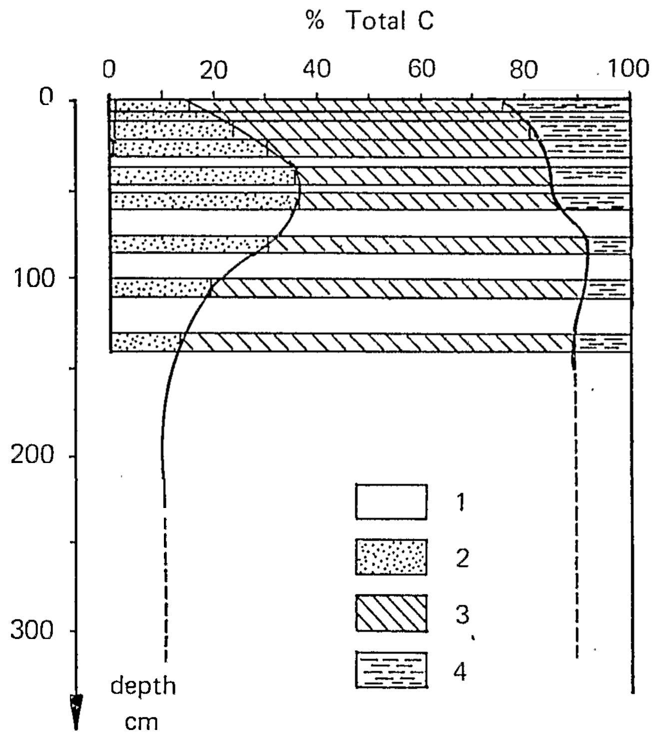

FIG. 4. — Variation in the relative content of the humic constituents with depth in < 2 mm fraction: 1, light organic residues; 2, free fulvic acids; 3, humin; 4, alkaline soluble fulvic and humic acids.

In the present study we obtained 120 tC/ha for the 0-100 cm layer and 170 tC/ha for the 0-200 cm layer, which is quite close to the maximum found in the literature.

Our results show, however, that the published values underestimate the real values in the acid clay latosol. In such a soil, the 0-100 cm layer contains only 50 % of the total carbon. Therefore the deep layers should not be neglected.

3.3.2. *Nature of organic products in the < 2 mm fraction*

The humus is rich in free fulvic acids in the 20-80 cm layer (fig. 4). The proportion of free fulvic acids decreases with depth.

In the whole soil the light organic residues represent less than 1 % of the total carbon (fig. 5, table V); we also estimate that the humin represents 66 % and the extractable fractions 33 % of the total carbon (20 % are free fulvic acids and 13 % alkaline-soluble fractions).

3.3.3. *Carbon in the > 2 mm fraction*

The carbon in this fraction is exclusively living and dead roots, which are found mainly in the upper part of the soil (fig. 3, table IV). It is noted that 75 % of the total is located in the first 50 cm and 90 % in the first 100 cm. Plant fragments are also found at greater depths. Thus, between 100 and 500 cm, there is 1 tC/ha of small roots.

If to the above total we add the light organic residues of the < 2 mm fraction *i. e.* (7.9 + 1.4) = 9.3 tC/ha; using the 0.45 coefficient we obtain approximately 21 t roots/ha, which is close to the value found for the ferrallitic soils of the southern Ivory Coast (HUTTEL, 1975).

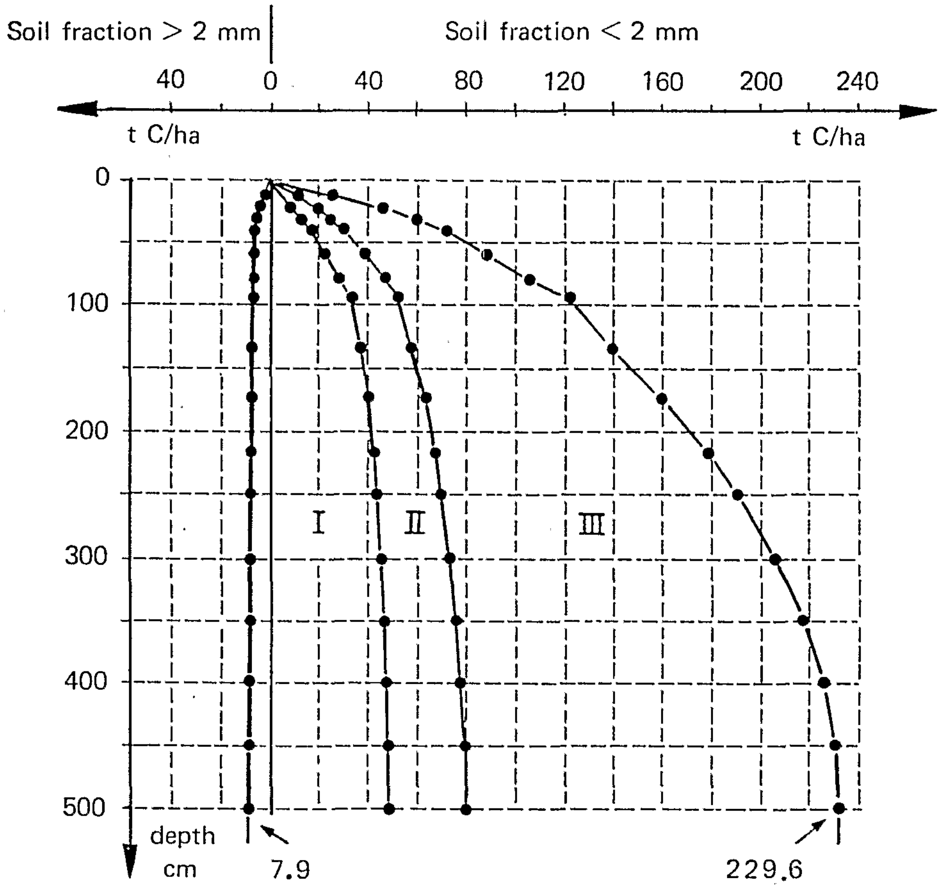

FIG. 5. — Cumulative quantities of carbon with increasing depth: carbon of soil fractions < 2 mm and > 2 mm. Carbon distribution in humic constituents: I, free fulvic acids; II, alkaline soluble fulvic and humic acids; III, humin.

4. — CONCLUSION

Morphological, physical, chemical and mineralogical properties of a single soil profile of a clayey latosol of the Manaus region were determined. The results show that in this situation the total carbon as soil humus represents 230 t/ha and most of this carbon is non-extractable (humin), with the remainder in the form of humic products easily solubilized or dispersed. Carbon as plant roots represents 9.3 t/ha and litter was equivalent to 3.6 tC/ha. Organic carbon was found at 300 cm. There are indications that the concentration of carbon is negligible only at 500 cm depth. Fine roots were found in the whole profile.

TABLE V. — *Carbon distribution on humic components of < 2 mm soil fraction (*LR, *light organic residues;* FFA, *free fulvic acids;* SAL, *alkaline soluble fulvic and humic acids;* H, *humin).*

Horizon	depth cm	LR		FFA		SAL		H		Total carbon (CT)	
		gC/m^2	%CT	gC/m^2	%CT	gC/m^2	%CT	gC/m^2	%CT	gC/m^2	%CT
A e B_1	0- 35	70	1	1500	23	1250	19	3750	57	6570	100
B_2	35-150	40	-	2280	27	1000	12	5100	61	8420	100
B_3	150-500	30	-	900	11	840	11	6200	78	7970	100
Total	0-500	140	1	4680	20	3090	13	15050	66	22960	100

These results are consistent with eluviation of organic carbon and storage of this carbon as humus within a significant part of the soil profile.

In the same Amazon forest of the Manaus region the total biomass had been estimated at 200-225 tC/ha (KLINGE, 1975) and the dead plant matter at 15 tC/ha. For a total of 215 to 240 t/ha, carbon in the living and dead vegetation is equal to the total carbon stored in the soil as humus.

These results have several implications, and future studies of the global ecology of the amazonian region, of soil formation and soil dynamics, and of forest-ecosystems or alterated ecosystems, must take them in account.

A. In a regional or global ecological perspective, the soil represents a large reservoir for carbon. It plays an important role in the relationships among terrestrial organismes and their physical-chemical environment. Thus we may need models which integrate such factor. But for this, processes should be understood and rates quantified.

In the central amazonian situation analyzed here, it is possible that a great part of the extractable humic fractions, mainly up to 150 cm deep, might be related to the soluble products transferred to depth from plants and litter. But the presence of deep roots suggests that there is also a direct incorporation of carbon into the soil by roots. For the time being, no evaluation of the relative importance of each source can be made.

The carbon balance in the soil is not known. A knowledge of the CO_2 release and of the turnover rates of humic fractions, especially that of the lower soil layers, is required. The residence time of this carbon in the soil is also unknown. In addition, fluxes of elements leached to ground and surface waters must be determined.

B. Carbon transfers at depths could have implications in soil transformations and some processes of soil formation. Humic acids will cause geochemical alterations that might explain, for example, the origin of some amazonian podzols and their genetic relationships with clayey yellow latosols (LUCAS *et al.*, 1984).

C. In a forest ecosystem, the biotic processes might represent significant controlling points in the cycling of mineral elements. However, under an amazonian forest cover the soil does not contain any appreciable quantities of reserves of plan nutrients. All soluble substances liberated in the soil by the weathering processes have been washed out. Nutrients are immediately re-absorbed from the forest litter which rapidly decomposes under the hot, wet climatic conditions (STARK, 1971). In these conditions the forest does not depend on the soil. It only stands on the soil and does not use the soil as a source of nutrients. The dense root-net of the forest trees acts as a highly effective filter which retains all dissolved substances, returning them immediately to the living trees without spillage into the groundwater (SIOLI, 1984).

Thus there is evidence that nutrients are not stored in the soil organic matter and that humic components of the soil, and the biotic processes within the soil, apparently are not linked with any nutrient supply or nutrient cycling. Soil organic matter appears to be an inert component, or perhaps a negative factor, because of its acidity and chemical affinity with the phytotoxic aluminium cation. The effects of changing systems of land use in the amazonian region on the dynamics of soil humus are largely unknown.

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