

## Nature and behaviour of organic matter in soils under natural forest, and after deforestation, burning and cultivation, near Manaus

Carlos C. Cerri<sup>a</sup>, Boris Volkoff<sup>b</sup> and Francis Andrieux<sup>c,\*</sup>

<sup>a</sup>Centro de Energia Nuclear na Agricultura (CENA, USP)CP96, 13400 Piracicaba, SP, Brazil

<sup>b</sup>Institut Français pour le Développement en Coopération (ORSTOM), BP 1857 Yaoundé, Republic of Cameroun

<sup>c</sup>ORSTOM Antena et CENA, Piracicaba, SP, Brazil

### ABSTRACT

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In a yellow Latosol from the Central Amazon rain forest, the amount of organic carbon within a 5-m depth is 240 t/ha, of which 120 t/ha are concentrated in the first 1 m of soil. Organic matter reflects soil conditions, and reacts quickly to external influences. This happens in the case of agricultural use, which frequently implies burning of the forest phytomass and litter. Lysimeter studies show that burning and subsequent decomposition of above-ground organic residues result in a loss of water-soluble nutrients, mainly nitrate and mineral cations, together with soluble organic anions. Even though a well-managed pasture of *Brachiaria humidicola* was installed following burning, the organic-matter content of the 0-0.20-m soil layer decreased by 25% in two years, because the decomposition of humus of forest origin was faster than the input of humus of pasture origin. After this time, these two processes were reversed, and soil organic-matter content was restored in about eight years. Natural carbon-13 measurements show that the proportion of soil carbon of grass origin was about 20% after two years, and 50% after eight years of pasture.

### INTRODUCTION

The Amazon Basin presents a large diversity of soils, of which more than 80% belong to the ferallitic or lateritic types (Sombroek, 1984; Volkoff, 1984). In these soils, and under native tropical rain forest, root activity is concentrated in the soil surface, and nutrient cycling occurs mainly from the above-ground decomposing litter (Schubart et al., 1984). After clear-felling and burning the forest, either for shifting agriculture or any other purpose, this

\*Permanent address: Centre de Pédologie Biologique, CNRS BP 5 54501 Vandoeuvre-lès-Nancy, France.



fragile equilibrium is destroyed, and the nutrients which are not absorbed by a replacing plant cover are leached out and irreversibly lost (Sanchez et al., 1982).

Deforestation strongly affects carbon (C) cycle, through the decrease of growing phytomass and above-ground residues (Fearnside, 1985). Total below-ground C content also decreases, and humus composition changes, in close relation with decreasing soil porosity, structural stability, and fertility. A comprehensive survey of such changes following annual crops was realized in the eastern Amazon by Martins and co-workers (1987, 1990). Data on the effects of cultivated pastures on the characteristics of soils from the Amazon Basin are also available (Falesi and Veiga, 1986). In the Manaus region, Teixeira (1987) studied the changes in soil nutrient content in a yellow Latosol under a young cultivated pasture of *Brachiaria humidicola*.

All authors agree with the fact that one of the main causes of pasture failure in Amazonia is probably the lack of nutrients, especially phosphorus, in relation to the density of grazing animals. Because in most soils of the humid tropics, soil organic matter (SOM) is the main exchange surface, a relationship between the development of the pasture and soil C content is expectable. The present work, which has also been carried out in the Manaus area, aims at establishing a balance-sheet of organic C in above-ground residues and surface humus, after deforestation and pasture cultivation. Losses of soluble C and mineral nutrients were estimated using a lysimeter. Further losses and inputs of C of forest and pasture origin were determined on the basis of carbon-13 ( $^{13}\text{C}$ ) natural abundance measurements.

#### MATERIALS AND METHODS

##### *Study area and soils*

Two even areas of clay-rich yellow oxisols – 'Latosolo amarelo muito argiloso', or 'Xanthic Ferralsol' – were selected in the Fundação de Apoio ao Distrito Agropecuário experimental farm (Site 1), and in the zootechnology farm of the Empresa Brasileira de Pesquisa Agropecuária (Site 2), located at km 39 and 56 of the Manaus/Boa-Vista Highway, respectively. An additional sampling area was located at the neighboring Bacia modelo forest reserve (Site 3). The soil of these areas is representative of those developed on uplands of a tertiary sediment material belonging to the Barreiras complex, and represents more than 10% of the total basin area. This material is predominantly kaolinitic, and produces low amounts of nutrients upon weathering (Anonymous, 1978; Ranzani et al., 1983; Lucas et al., 1984). The native vegetation is a dense rain forest on 'terra firme' (upland), in which the highest trees reach 35 m, and the shrub level is dominated by several palm-tree species (Guillamet, 1987). The distribution of total and humus C in these soils was

studied previously by Volkoff et al. (1982), and Cerri and Volkoff (1987). A quantitative study of root material and of microbial and faunal biomass in the soil of a neighboring site was published by Chauvel et al. (1987).

On site 1, three areas under native forest, recently burned forest, and one-year-old pasture were chosen. The three areas selected on site 2 were under native forest, two-year-old pasture, and eight-year-old pasture. Litter and soil samples from site 3 were used for the characterization of native SOM.

#### *Soil organic carbon fractionation and analysis*

The native forest litter was sampled in triplicate on sites 1, 2 and 3, and the above-ground residues remaining after recent burning and pasture cultivation on site 1 were collected in duplicate, using a 1-m<sup>2</sup> frame. These materials were air-dried, weighed, and manually separated into leaf fragments, wood fragments, roots, charcoal, soil aggregates, and unidentified residues. Each of these fractions was carefully weighed, then ground to a 50- $\mu$ m cut-off. From three to four layers were distinguished within the 0–0.20-m layer of each soil, and sampled in duplicate. Bulk density was measured on undisturbed clods of each layer, in order to transform their C contents from percent weight to t/ha. The loose soil material was calibrated by 2-mm sieving, then an aliquot was ground to 50  $\mu$ m, and another aliquot was extracted with 0.10M sodium pyrophosphate, according to Dabin (1971), in order to separate alkali-soluble SOM. Organic C contents were determined on solid samples of plants, soils and soil extraction residues by combustion in an open-oven analyzer, and on the alkaline extracts by dichromic acid oxidation.

#### *Soil natural water sampling and analysis*

In site 1, under native forest and on the bare soil, lysimeters were installed in January 1987, immediately after burning the cut aerial biomass. These systems consisted of PVC cylinders, 0.13 m in diameter, and 0.30 m or 1.30 m in height. Soil water percolating through the 0–0.20-m and 0–1.20-m soil layer, according to their respective length, was collected after each rain event, i.e. daily or twice a day during the January–June rainy season (Andreux et al., 1987). Soluble cations were determined by atomic absorption or by plasma spectroscopy, and soluble sulfate, chloride, nitrate and nitrite were determined by flow injection and colorimetry in the Radiochemistry Section of CENA.

Dissolved organic carbon (DOC) and bicarbonate C were determined after combustion and methanization with a commercial autoanalyzer, in the Soil Organic Matter Section of the Centre de Pédologie Biologique at Vandoeuvre, France.

### Natural carbon-13 analysis

Natural abundances of  $^{13}\text{C}$  isotope were determined by mass spectrometry on the purified  $\text{CO}_2$  produced by combustion of soil sample in sealed pyrex tubes in the presence of  $\text{CuO}$  catalyst, according to the procedure used at the Department of Stable Isotopes of CENA (Volkoff et al., 1982). The natural abundance of each sample was expressed in delta ( $\delta$ ) units, by reference to the international standard PDB, as follows:

$$\delta^{13}\text{C}\text{‰} = ((^{13}\text{C}:^{12}\text{C})_{\text{SP}} - (^{13}\text{C}:^{12}\text{C})_{\text{PDB}}) \times 1000 / (^{13}\text{C}:^{12}\text{C})_{\text{PDB}}$$

Natural variations of  $\delta^{13}\text{C}$  values in plants are due to the fact that, during  $\text{CO}_2$  assimilation, plants discriminate the stable isotope  $^{13}\text{C}$  to a different extent, according to their  $\text{C}_3$ ,  $\text{C}_4$  or CAM photosynthetic pathway (Bender, 1971; Smith and Epstein, 1971). As a result, the isotopic composition of soil organic C can be modified (Deines, 1980). Measurements of  $\delta^{13}\text{C}$  values in soils and soil fractions were used to calculate the distribution of SOM of forest ( $\text{C}_3$ ) and culture ( $\text{C}_4$ ) origin, on the basis of earlier findings by Cerri et al. (1985), Cerri (1986), Balesdent et al. (1987), and Andreux et al. (1990). Detailed results obtained in the present case of a pasture of *B. humidicola* were extensively discussed by Choné et al. (1990).

Organic C of forest ( $\text{C}_f$ ) and pasture ( $\text{C}_p$ ) origin are calculated as follows:

$$C_s \times \delta^{13}C_s = C_f \times \delta^{13}C_f + C_p \times \delta^{13}C_p$$

where  $C_s$  is the total C content of the soil sample collected under pasture, and  $\delta^{13}C_s$ ,  $\delta^{13}C_f$  and  $\delta^{13}C_p$  the respective  $\delta^{13}\text{C}$  values (in ‰) of the soil sample collected under pasture, of the corresponding soil sample collected under native forest, and of a blended sample of the pasture vegetation.

## RESULTS AND DISCUSSION

### *Distribution of above- and below-ground organic carbon*

#### *Soils under native forest*

In the studied area, the aerial forest phytomass is about 200–225 t C/ha, and the litter production reaches 5–6 t C/ha (Klinge et al., 1975). About 240 t C/ha are present in the first 5 m of the soil profile, with only 120 t C/ha in the first 1 m (Cerri and Volkoff, 1987). Table 1 shows the detailed distribution of surface organic C on site 1. In the 0–0.20-m soil layer, the amount of C in the fractions of residues coarser than 2 mm is close to that in the litter. However, these materials account for less than 10% of the total organic C present within this layer. Alkali-extractable SOM accounts for 11 t C/ha, but

TABLE I

Distribution of organic carbon (t/ha) in above-ground residues and soil humus (0–0.20-m layer), under native and burned forest, and after pasture installation on site 1 (February 1987)

Fractions	Native forest	Burned forest	Pasture (18 months)
Leaves	2.3	0	3.1
Wood fragments	2.7	1.5	0.5
Litter roots	0.2	0.2	0.2
Charcoal	0	2.5	0.5
Aggregates	0.1	1.8	0
Unident. fragments	1.2	3.6	1.4
Whole residues	6.5	9.6	5.7
> 2-mm fragments	5.1	4.9	3.7
< 2-mm fragments	14.0	7.0	9.0
> 2-mm roots	2.0	1.8	1.1
Extractable humus	11.0	10.0	6.0
Unextractable humus	44.0	40.0	39.0
Whole 0–0.20-m soil	73.1	63.7	58.8
Total residues and soil	79.6	73.3	64.5

it was found (Cerri and Volkoff, 1987) that acid-soluble free fulvic acids increased from 15 t C/ha in the 0–0.20-m layer to 23 t C/ha in the next soil 1 m.

#### *Soils under burned forest and young pasture*

Although deforestation and burning destroy aerial phytomass and a large proportion of forest litter (Fearnside, 1987), the amount of above-ground residues is greater after than before burning (Table 1). All leaf material has disappeared, and a large proportion of charcoal, imperfectly burned wood, and loose soil aggregates predominates. Comparatively, only slight changes occur in soil organic C.

After pasture installation, the amount of above-ground residues has still decreased. A fast decomposition of wood residues seems to have occurred, but is not compensated by the humification of graminaceous litter. In the upper soil layer, the proportions of coarse residue and roots are also lower than immediately after burning, and a slight tendency to a decrease of total and extractable SOM C content is noticed.

#### *Composition of soil water*

The volumes of soil solution collected with the lysimeters are rather similar to those of the precipitation measured in the meantime. A negative difference

in relation to precipitation volumes (Table 2) occurs when the rain event follows a dry period of more than one day, and can be explained by evaporation or water retention by the soil. From this viewpoint, only small differences are observed between water samples collected under native and burned forest. Using plate lysimeters (Andreux et al., 1987; Chauvel et al., 1989), it was noticed that the volumes collected below 0.50 m were generally less than, and independent from, the respective amounts of precipitation, due to a pre-*existing* lateral migration of soil water.

The pH values of the solutions collected at 0.20 m are less than those of the solutions collected at 1.20 m, probably due to the presence of greater accumulations of organic acids in the top soil. Only in the solutions collected at 1.20 m, pH values are higher under the burned forest than under the native one. The dry-weight of total mineral matter (TMM) present in the leachates is greater in the solutions collected at 0.20 m than in those collected at 1.20 m, which suggests that part of the material solubilized in the top soil re-precipitates in the sub-soil. A significant correlation ( $r=0.78^*$ ) was observed

TABLE 2

Volumes of precipitation and of soil solutions collected in February, 1987, under native and burned forest, and variations of pH and dissolved mineral-matter weight (Site 1).

	Rain period				Total
	27/01-03/02	06/02-11/02	13/02-19/02	21/02-01/03	
<b>Rain (mm or L/m<sup>2</sup>)</b>	117.0	76.5	70.7	92.3	307.0
<b>Soil solution (L/m<sup>2</sup>)</b>					
Native forest					
0-0.20 m	110.1	57.7	69.5	49.3	286.6
0-1.20 m	92.4	57.6	54.1	40.8	244.9
Burned forest					
0-0.20 m	98.4	64.4	84.0	42.1	288.9
0-1.20 m	103.0	61.0	87.0	40.6	291.6
<b>pH range</b>					
Native forest					
0-0.20 m	3.9-4.3	3.9-4.1	3.8-4.1	4.0-4.4	3.8-4.4
0-1.20 m	4.7-5.7	5.1-5.6	5.0-5.7	5.1-5.8	4.7-5.8
Burned forest					
0-0.20 m	3.8-4.1	3.9-4.2	3.9-4.2	3.9-4.4	3.8-4.4
0-1.20 m	5.7-6.7	4.9-6.3	5.1-5.9	5.6-6.3	5.1-6.7
<b>Mineral matter (g/m<sup>2</sup>)</b>					
Native forest					
0-0.20 m	2.28	1.63	1.86	1.18	6.95
0-1.20 m	0.51	0.13	0.31	0.45	1.40
Burned forest					
0-0.20 m	3.50	2.31	2.63	1.06	9.50
0-1.20 m	1.22	0.53	1.19	0.76	3.70

between the daily amounts of TMM and the volumes of leachate at 0.20 m, with no respect to the either native or burned site (Andreux et al., 1987). The mean amount of TMM is about 1.5 and 3 times less under native than under burned forest at 0.20 and 1.20-m depths respectively.

Regarding the ionic balance-sheet, Table 3 indicates that the cation concentration in solutions collected at 0.20 m is about the same in both native and burned systems. However, these solutions differ by a larger concentration of Na, and a lower concentration of K and Ca, under native than under burned forest. Aluminium always predominates, but Fe and Mn hardly exceed 0.5  $\mu\text{eq/L}$ , in relation to the low Fe content, which is generally lower than 1000 ppm in these soils (Sombroek, 1984). In solutions collected at 1.20 m, a striking difference is observed concerning Na concentration, which is about four times higher under the burned forest. At this depth, Al is detected only in the burned system, and at much smaller concentrations than at 0.20 m.

TABLE 3

Mean chemical composition of soil water collected with tube lysimeters at 0.20 and 1.20 m under native and burned forest, in February, 1987 (SD in parentheses)

	Cations ( $\mu\text{eq/L}$ )							monovalents/ polyvalents
	H	Na	K	Ca	Mg	Al	Sum	
<b>Native forest</b>								
0-0.20 m	93 (28)	227 (134)	41 (31)	43 (22)	73 (37)	297 (140)	878 (297)	1.3
0-2.20 m	6.7 (4.4)	23 (13)	3.7 (1.0)	18 (17)	9 (4.5)	nd	86 (71)	2.3
<b>Burned forest</b>								
0-0.20 m	95 (31)	72 (15)	90 (34)	164 (52)	81 (23)	312 (140)	859 (270)	0.6
0-1.20 m	2.8 (3.1)	270 (58)	9.4 (8.2)	29 (25)	11 (7)	33 (66)	266 (61)	12.5
	Anions ( $\mu\text{eq/L}$ )					Dissolved carbon (mg/L)		
	$\text{NO}_3^-$	$\text{Cl}^-$	$\text{SO}_4^{2-}$	Sum	Deficit	Organic C	Mineral C	
<b>Native forest</b>								
0-0.20 m	118 (75)	76 (28)	21 (21)	201 (85)	744 (234)	57 (91)	6 (8.5)	
0-1.20 m	28 (50)	8.6 (2.9)	n.d.	31.7 (23.7)	56 (47)	3.0	n.d.	
<b>Burned forest</b>								
0-0.20 m	135 (60)	32 (9)	15 (30)	157 (71)	614 (189)	35 (44)	8.8 (0.4)	
0-1.20 m	57 (31)	28 (11)	n.d.	82 (31)	177 (121)	3.2	n.d.	

In some cases, mineral anions perfectly balance cationic charges. The nitrate ion hardly exceeds 200  $\mu\text{eq/L}$ , even in water collected at 0.20 m under burned forest, in which it reaches its maximum values. The chloride concentration is rather constant at 0.20 m and 1.20 m in the burned forest. Chloride is mainly brought by the rain itself, with a noticeable influence of canopy throughfall, as observed by Franken et al. (1987). However, it seems that the influence of marine salt aerosols cannot explain the large amounts of soluble Na, which results mainly from plant biological cycling, and migrates quickly after clearing.

The deficit of anions is similar in solutions collected at 0.20 m from both native and burned systems, but it is greater at 1.20 m in the burned than in the native system. From 0 to 120 mg DOC/L (with an average negative charge density of 4–10  $\mu\text{eq/g C}$  (Andreux, 1982)), and up to 12 mg/L of bicarbonate C (with a charge density of 80  $\mu\text{eq/g}$ ) are present in the colourless solutions collected at 0.20 m from both systems. This means that organic anions balance the cationic charge in solutions leached from the surface horizons, and that both organic and bicarbonate anions are involved in the migration of Na and other nutrients, which occurs at higher pH values after burning. Assuming that the mean DOC concentration in soil solution remains constant during the whole rainy period, it can be assessed that about  $1 \times 10^3$  t C/ha are annually leached out from the 0–0.20-m soil layer in the burned system.

#### *Distribution of humus of forest and pasture origin*

Table 4 shows that, during the first and second years following deforestation, the contents of total humus C and forest-derived C decrease continuously, and faster than the input of pasture-derived C, which reaches 5% and

TABLE 4

Carbon-13 abundances ( $\delta^{13}\text{C}$ ), total carbon in humus ( $C_s$ ), and percentages of carbon from forest and pasture in the 0–0.20-m layer of the yellow Latosol

Site	$\delta^{13}\text{C}$ (‰)	Humus $C_s$ (t/ha)	Carbon from forest		Carbon from pasture
			(% init. C)	(% $C_s$ )	(% $C_s$ )
<b>Site 1</b>					
Natural forest	-27.8	66	100	100	0
Bd. forest	-27.4	57	86	100	0
1-year pasture	-27.1	54	77	95	5
<b>Site 2</b>					
Natural forest	-27.8	90	100	100	0
2-year pasture	-24.7	67	61	79	21
8-year pasture	-20.7	96	56	52	48



21% of total humus C after one and two years, respectively. In absolute values, the amount of C of pasture origin which accumulates in the 0–0.20-m layer is about 2.7 t/ha after one year in site 1, and 14 t/ha after two years in site 2. Such a high value is likely only if grazing was limited during the corresponding period, especially in view that C input during the two first years is mainly due to the decomposition of grass aerial parts, rather than of root deposits. During the following years, the opposite occurred, and a faster increase in the proportion of pasture-derived C in the 0.10–0.20-m layer than in the 0–0.20-m layer was observed (Choné et al., 1990). After eight years of pasture, the C content in the 0–0.20-m layer is again close to its initial value in the corresponding soil under native forest. This again corresponds to an average annual C input of about 5 t/ha, which is unusually high, and indicates a rather exceptional management of the pasture.

The fast decrease of forest-derived humus C during the first two years contrasts with its relative stability during the next period. It is probable that removal of organic C by water leaching through the bare soil continued until the installation of the grass cover stopped it. However, these C losses by solubilisation hardly exceed 1 t/ha, and are relatively low compared with losses by mineralization. It can be thought that the grass root activity stimulates microbial species which are much less adapted to the degradation of lignin-related compounds than those of the native forest soil.

After eight years of pasture, about one half of the initial forest-derived humus C is still present in the soil. Whether this humus is inactive or still has a role in the maintenance of soil and pasture is not known, but it is important to observe that a successful installation of pasture certainly tends to limit soil organic C exhaustion.

#### CONCLUSION

The quick response of soil organic matter to external influences such as deforestation makes it a powerful tool to track related soil changes; mineralization and eluviation processes are no longer balanced by litter fall and decay, resulting in a subsequent decrease of soil humus content. Losses of humus C of forest origin take place mainly during the first and second years following clearing and installation of cultivated pasture. During the next years, total soil humus C content rises again to its initial value, as a consequence of increasing humification of grass root deposits.

It is important to mention that these results were obtained in an almost ideal well-managed pasture area, and that an eight-year survey is probably not sufficient to predict soil organic matter content and soil behaviour in the forthcoming ten years. Long-term integrated studies under different conditions of topography and soil type are needed, in order to establish to what

extent such changes of plant cover can prevent the soil from further degradation of its physico-chemical and agricultural properties.

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