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Publication information

Geoderma (ISSN 0016-7061). For 1994 volumes 58–62 are scheduled for publication. Subscription prices are available upon request from the publisher. Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by surface mail except to the following countries where air delivery via SAL is ensured: Argentina, Australia, Brazil, Canada, Hong Kong, India, Israel, Japan, Malaysia, Mexico, New Zealand, Pakistan, PR China, Singapore, South Africa, South Korea, Taiwan, Thailand, USA. For all other countries airmail rates are available upon request. Claims for missing issues must be made within six months of our publication (mailing) date. Please address all your requests regarding orders and subscription queries to: Elsevier Science B.V., Journal Department, P.O. Box 211, 1000 AE Amsterdam, The Netherlands. Tel.: 31-20-5803642, fax: 31-20-5803598.

(continued on inside back cover)

Geoderma, 61 (1994) 103–118
Elsevier Science B.V., Amsterdam

Organic carbon and ^{13}C contents in soils and soil size-fractions, and their changes due to deforestation and pasture installation in eastern Amazonia

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(Received May 6, 1992; accepted after revision April 5, 1993)

ABSTRACT

In soils of the eastern Amazonian forest, modifications in soil organic matter (SOM) contents as a consequence of deforestation and pasture installation were investigated. Profile distribution of total organic carbon (C) and nitrogen (N), and of ^{13}C isotope abundance (expressed in $\delta^{13}C$‰ units) were compared. The two soils, one under native forest and the other one after ten years under pasture of *Pennisetum purpureum* had similar C/N values, which slightly decreased with increasing depth, from 13.6 to 11.9–12.7 within the first 40 cm. In the pasture soil, the C content was slightly lower than in the forest soil, and reached 29 t ha^{-1} compared with 31 t ha^{-1}, and 15 t ha^{-1} compared with 16 t ha^{-1}, in the 0–20 and 20–40 cm layers, respectively.

The $\delta^{13}C$ values reflected the origin of SOM, from either the forest (which had a C3 photosynthetic cycle), or the pasture (which had a C4 cycle). They were higher by at least 6.5 and 1.5 units, in the respective 0–10 and 10–20 cm layers of the pasture soil, than in the corresponding layers of the forest soil. These $\delta^{13}C$ values were used to estimate the proportions of C derived from the forest (Cdf) and from the pasture (Cdp). The calculations clearly indicated a strong input of Cdp, which reached 46–49% and 21–24% of total C in the respective layers.

Particle size fractionation showed that SOM changes were predominant in the upper soil layer (0–10 cm), and vanished with increasing depth: in the pasture soil, the coarse organic residues accumulated, whereas the amount of C in the finest fractions decreased, which suggested a slowing down in humification processes. In the forest soil, the $\delta^{13}C$ values were lower in the coarsest than in the finest fractions, the latter being less affected than the coarsest ones by the vegetation change; in the 0–10 cm layer, these values increased by about 7–10 units in the sand-size fraction, and only 4–5 units in the clay-size fraction. Thus, the replacement of Cdf by Cdp was greater in the sand-size fraction (55–65% of total C), than in the clay-size fraction (34–45% of total C). Based on ^{14}C dating, the oldest pool (i.e. that of mean age 5000 years) of forest SOM was calculated at each depth. In the soil surface, it was still smaller than the more labile fraction of Cdf, and represented about 17% and 26% of total C in the 0–10 cm and 0–20 cm layers, respectively.

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SSDI 0016-7061(93)E0046-X

H0554

INTRODUCTION

Soil organic matter (SOM) is considered to have an essential role in soil properties and in soil–plants–organisms interactions (Oades, 1989). It governs the structure stability in surface soil layers, either directly, through its chemical structure and surface properties, or indirectly, as a source of energy and nutrients for soil biota (Allison, 1973; Emerson et al., 1986). These effects are especially marked in cultivated tropical soils, in which the control of SOM contents has received an increasing concern in the last few decades, especially because it was reported to be frequently related to soil fertility and productivity (Nye and Greenland, 1964; Sanchez et al., 1983).

Since the end of the 1960's, deforestation and agricultural practices have been strongly increasing in the tropics, especially in the Brazilian Amazon basin, where about 100,000 km^2 of grazing pasture have been installed (Salati and Vose, 1984; Malingreau and Tucker, 1988). In many cases a subsequent degradation of soil quality is either reported or feared (Fearnside, 1980; Falesi and Veiga, 1986; Martins et al., 1991), although little is still known about the qualitative changes that accompany the observed decreases in SOM contents, neither about the extent of the reversibility of such decreases from one place to another.

In eastern Amazonia, the fragility of Ultisols and related soils, especially in terms of structure stability and hydric balance is well known (Martins, 1987). In these soils, losses of SOM, and decreases in fertility following clear-felling and annual cropping practices have been reported (Martins et al., 1991), whereas the impact of cultivated pastures in the same sites has been less studied. The aim of this paper is to fill this gap by assessing the changes which may have occured in SOM contents in these soils 10 years after pasture installation. Organic carbon (C) and nitrogen (N) contents in soil layers and in their particle-size fractions will be compared with those in the respective layers and fractions of the forest soil. Thereafter, natural ^{13}C abundance measurements and ^{14}C dating will be used, to determine and discuss the inputs and transfers of SOM of both plant origins that have occurred during the referred period of time.

MATERIALS AND METHODS

Study site and sampling

The study was carried out at the experimental farm of the "Empresa Brasileira de Pesquisa Agropecuaria" (EMBRAPA) near Capitão Poço, in the northeast of the state of Para (1°44′ S; 47°09′ W). This area receives a mean annual rainfall of 2500 mm and the monthly mean temperature varies from 25.5°C in January to 27.9°C in July (Rego et al., 1973). The natural vegetation is an evergreen lowland rainforest (Dantas et al., 1980). Site descriptions were detailed in earlier works by Martins and Cerri (1986) and Desjardins (1991).

The soils developing on Tertiary sediments of the Barreiras formation (Nunes et al., 1973), were predominantly medium textured *"Latossolos podzolisados"* according to the Brazilian classification, and were tentatively classified as *"Typic Kandiudults"* in the US Soil Taxonomy (Soil Survey Staff, 1990). The topography was very slightly undulated, and the soils presented noticeable local changes in mottling intensity, bulk density and texture. Two areas were sampled, the first one under native forest, and the second one under a ten year old pasture of elephant grass (*Pennisetum purpureum*) which was located 800 m away from the forest area. In this area, deforestation was carried out in a traditional way. At the end of the rainy season, economically important trees were removed, then the remaining vegetation was cleared, the felled material was piled, allowed to dry on site, and burned. A few months after burning, the pasture was planted, rather than sown, using three knot-cuttings. No tillage was applied, but planting was repeated twice a year, at least during the first years. Minimal N, P, K fertilization was probably applied, but no detailed record was kept at the farm regarding this point. The area was mainly used as a fodder reserve, and no cattle had grazed on it during the last years before sampling.

The main characteristics of the topsoils, shown in Table 1, indicate that the physical characteristics of the two soils were quite similar. Their texture was sandy loam in the A horizon, with a sharp increase in the clay content with increasing depth. Due to burning and fertilization, their chemical characteristics were different, especially the values of pH and base saturation which

TABLE 1

Main analytical characteristics of soils from the two study sites

Depth (cm)	pH H_2O	ECEC (meq 100 g^{-1})	Base sat. (% ECEC)	Texture (%)			Bulk density	Carbon (mg g^{-1})	Nitrogen (mg g^{-1})	C/N
				Sand	Silt	Clay				
Forest soil										
0–3	4.4	2.69	66.9	–	–	–	1.10	20.9	1.54	13.6
3–10	3.8	1.63	33.1	72.6	8.9	18.5	1.28	13.7	1.09	12.6
10–20	3.9	1.39	25.9	68.7	6.9	24.4	1.44	8.5	0.69	12.3
30–40	4.1	1.17	18.8	61.1	9.7	29.2	1.63	4.3	0.36	11.9
Pasture soil										
0–4	5.4	5.85	98.1	–	–	–	1.07	20.9	1.50	13.6
4–10	5.5	1.68	86.9	77.2	9.6	13.2	1.30	11.8	0.86	13.6
10–20	5.1	1.36	83.8	70.0	13.4	16.6	1.56	7.4	0.59	12.2
30–40	4.9	1.01	67.6	63.3	15.3	21.4	1.67	4.0	0.35	12.7

were higher in the pasture soil than in the forest soil, and than in neighbouring soils left fallow after a few years of annual cropping (Diez et al., 1991; Martins et al., 1991). Additionally, in the pasture soil, a tendency to a temporary waterlogging was frequently observed.

A pit 250 cm long, and 200 cm deep was dug in each area, and 2–3 kg of soil were taken from the successive layers on one side of the pit (0–3 and 0–4 cm, 3–10 and 4–10 cm, under forest and pasture, respectively, then every 10 cm in both areas). The samples were air-dried, sieved through a 2 mm sieve, and homogenized manually. The forest litter was collected in quadruplicate, using a wooden frame of 2500 cm^2. The undecomposed and decomposing leaves on the one hand, and the unidentified coarse organic material (500–2000 μm) on the second hand, were separated, dried at 50°C and finely crushed, using an electric mill.

Particle-size fractionation

Fifty grams of air-dried 0–2 mm sieved soil were first dispersed by mechanical shaking in 150 ml of water in the presence of 5 mm glass beads, and using a low energy sonication (240 W, 25 kHz) during 3 min. Sand-size plant fragments were separated together with sandy minerals, by wet-sieving, successively at 212 μm and 53 μm. The coarse silt fraction (5–50 μm) and the fine silt fraction (2–5 μm) were separated by repeated sedimentation in water. The fractions coarser than 5 μm were oven-dried at 55°c. The fine clay (0–0.2 μm) and the coarse clay (0.2–2 μm) fractions were separated by centrifugation and freeze-dried. Prior to analysis, all fractions were ground by hand in an agate mortar.

Analytical methods

The total carbon (C) and nitrogen (N) contents were determined by dry combustion in a "Carlo Erba NA 1500" CHN autoanalyser. The plant and soil organic samples were mineralised in a pure oxygen atmosphere at 900°C in the presence of CuO as catalyst. The released CO_2 was then purified and injected in a "Finnigan Mat Delta E" mass spectrometer fitted with triple-ion collector and dual inlet system. Carbon-13 natural abundance on each sample was expressed in δ units, by reference to the international standard PDB (Craig, 1957), according to the following equation:

$$\delta^{13}C‰ = 10^3 \times [(^{13}C/^{12}C)_{sp} - (^{13}C/^{12}C)_{PDB}]/(^{13}C/^{12}C)_{PDB}$$

Samples were analysed at least twice until differences between repetitions where less than 0.3‰ δ units.

Radiocarbon measurements were carried out on five samples distributed between the surface and the 150–160 cm layer of the forest soil. The combustion and the conversion into benzene were run according to the method described by Guillet (1972). Liquid scintillation counting of the benzene was obtained after 24 to 48 hours, using a β Tri-carb Packard spectrometer (model 3003), and the results were expressed as follows:

$$\Delta^{14}C‰ = 10^3 \times (A_S/A_R - 1)$$

where A_S is the sample activity, and A_R is the reference activity. When $\Delta^{14}C$ values were negative, the results were also expressed as apparent ages. When $\Delta^{14}C$ values were positive, corresponding to modern materials, apparent ages were corrected, based on the contribution of thermonuclear ^{14}C (Délibrias, 1985).

Estimation of carbon derived from C3 and C4 plants

As shown by several authors (Cerri et al., 1985; Balesdent et al., 1987; Vitorello et al., 1989), ^{13}C natural abundance can be used to estimate the distribution of C from two sources in soils cultivated with C4 crops following deforestation. The method, based on the fact that plants with C3 and C4 photosynthetic cycles differ in their $\delta^{13}C$ (Bender, 1971; Smith and Epstein, 1971) and transfer these differences to SOM, has been extensively discussed by these authors and others (e.g. Balesdent et al., 1987; Andreux et al., 1990). Basic hypotheses and approaches, similar to those presented in the quoted studies, were developed in the present case.

Carbon derived from forest residues (Cdf) and from *Pennisetum* residues (Cdp) in any sample from a soil layer or SOM fraction of the pasture soil were expressed either as mg C g^{-1}, or as percent of total C (PCdf and PCdp) of the respective layer or SOM fraction, as follows:

$$Cdp = Cc.(\delta_c - \delta_f)/(\delta_p - \delta_f) \quad Cdf = Cc - Cdp$$

$$PCdp = 100.(\delta_c - \delta_f)/(\delta_p - \delta_f) \quad PCdf = 100 - PCdp$$

where Cc is the total C content of the sample from the cultivated soil (layer or fraction), δ_c is the $\delta^{13}C$ value of this sample, δ_f is the $\delta^{13}C$ value of sample from the corresponding forest soil layer or SOM fraction, and δ_p is the $\delta^{13}C$ value of selected *Pennisetum* residues, used as references.

The percentage of C from forest material lost since the installation of the pasture (PCdf-loss) was calculated as follows:

$$PCdf\text{-}loss = 100 - PCdf \times (Cc/Cf)$$

where Cc and Cf are the C contents of the respective cultivated and forest soils or soil fractions. Conversion of Cf and Cp from mg g^{-1} to t ha^{-1} in a given soil layer was made, using the following equation:

$$C(t\ ha^{-1}) = C(mg\ g^{-1}) \times d \times e \times 10$$

where d is the bulk density, and e is the thickness (in m) of the referred layer.

RESULTS

Distribution of total C in SOM fractions

The profiles under forest and under pasture are almost similar with regard to their total C and N contents (Table 1). The carbon concentration is higher than 20 mg g^{-1} in the first centimeters of the soils, then decreases sharply to less than 10 mg g^{-1} below 10 cm. Earlier studies (Desjardins, 1991) have shown that a quite constant value of 2.8 mg g^{-1} is attained at a depth of 100 cm on. The two soils layers have medium C/N values, which slightly decrease with increasing depth. When C is calculated on a soil volume basis, the cumulative C content of the 0–100 cm layer is slightly higher in the forest soil (81 t ha^{-1}) than in the pasture soil (77 t ha^{-1}). Almost 40% (31 and 30 t ha^{-1}, respectively) of this C are located in the 0–20 cm layer, and 20% (15 and 16 t ha^{-1}, respectively) in the 20–40 cm.

The particle-size fractionation yields rather similar weight distributions of solid fractions in the two soils: the coarse (50–2000 μm) fractions are always predominant, although the proportion of the coarse clay (0.2–2 μm) fraction starts to increase in the layers below 30 cm (Table 2). The size distribution of total C in the two soils is shown in Table 3. In the upper layer (0–3 cm) of the forest soil nearly one half (47%) of the C is present in the sand-size fractions (50–200 and 200–2000 μm); this proportion reaches 60% in the 0–4 cm layer of the pasture soil. With increasing depth, the proportion of total C becomes widely predominant in the clay-size fractions, especially in the coarse clay (0.2–2 μm) fraction. In the soil under pasture, the C content is higher in the coarsest (200–2,000 μm) fractions of the upper layers (0–4 and 4–10 cm), and in the 2–5 and 0.2–2 μm fractions of the 10–20 and 30–40 cm layers, than in the respective fractions of the forest soil. In all other fractions of the pasture soil, the C content is lower than in the corresponding fractions of the forest soil.

TABLE 2

Percent weight distribution of particle size fractions in the upper soil layers

Fraction (μm)	Site and depth (cm)							
	Forest				Pasture			
	0–3	3–10	10–20	30–40	0–4	4–10	10–20	30–40
200–2000	46	43	38	32	37	37	35	29
50–200	35	36	33	28	45	43	41	39
5–50	8	9	10	11	10	10	10	10
2–5	3	4	5	6	3	3	5	5
0.2–2	7	7	13	22	4	6	8	16
0–0.2	1	1	1	1	1	1	1	1

TABLE 3

Carbon contents (expressed in mg g^{-1} of fraction and in % of Ct) of the particle-size fractions of the two soils

Fraction (μm)	Unit	Site and depth (cm)							
		Forest				Pasture			
		0–3	3–10	10–20	30–40	0–4	4–10	10–20	30–40
200–2000	mg g^{-1}	8.5	3.1	1.6	0.7	15.7	4.8	1.4	0.6
	%	20	9	7	5	28	14	6	4
50–200	mg g^{-1}	15	11.2	3.9	1.2	14.9	8.4	3.2	0.7
	%	27	19	16	7	32	29	17	6
5–50	mg g^{-1}	49	32.4	15.7	5.8	36.1	25.6	15.3	4.8
	%	18	22	20	12	17	21	20	10
2–5	mg g^{-1}	81.2	56.2	30.7	17.7	66.6	54.9	37	20.8
	%	12	15	17	18	9	14	23	20
0.2–2	mg g^{-1}	51.8	40.6	22.8	12.6	48.6	41.9	29.3	16.2
	%	17	21	36	55	10	19	30	54
0–0.2	mg g^{-1}	131.1	144.7	111.4	94.9	116.6	84.7	55.4	40.7
	%	6	4	4	4	3	3	4	7

$\delta^{13}C$ values of plant and litter materials

The $\delta^{13}C$ values measured on green leaves and twigs of forest trees range from −37.7 to −31.2‰, while roots present less negative (−27.7‰) values. The $\delta^{13}C$ values of litter components show a slight increase with increasing decay, from −30.5‰ in undecomposed leaves to −29.6‰ in decomposing leaves, and −28.9‰ in the unidentified organic material. In *Pennisetum*, the leaf material has a higher $\delta^{13}C$ value (−11.2‰) than the corresponding root material (−13.0‰). These values, rather than their mean value (−12.1‰) were chosen for δ_p in further calculations.

$\delta^{13}C$ values of SOM and its particle-size fractions

The soils under forest and pasture have very different isotopic ratios in the upper layers (Table 4): in the forest soil these values range from −28.5‰ in the topsoil to −26.4‰ in the 50–60 cm layer, while in the pasture soil they decrease from −19.1‰ in the topsoil to −26.4‰ in the 50–60 cm layer. In the lower part of the two profiles the $\delta^{13}C$ values are quite similar, showing a

TABLE 4

^{13}C natural abundances (expressed in ‰ δ units) of the whole soils and of their respective particle size fractions

Fraction (μm)	Forest				Pasture			
	0–3	3–10	10–20	30–40	0–4	4–10	10–20	30–40
Whole soil	−28.5	−28.3	−27.7	−26.7	−19.1	−21.6	−23.9	−26.1
200–2000	−28.9	−28.4	−28.1	−27.6	−18.0	−21.2	−21.6	−22.5
50–200	−28.9	−28.6	−28.0	−27.0	−19.1	−21.4	−22.2	−24.6
5–50	−28.8	−28.6	−28.0	−26.9	−20.5	−22.3	−23.4	−26.2
2–5	−28.3	−28.0	−27.0	−24.1	−21.5	−23.0	−24.7	−25.3
0.2–2	−26.5	−26.6	−26.2	−25.6	−21.3	−22.0	−23.7	−24.9
0–0.2	−26.5	−26.1	−25.4	−23.4	−21.0	−21.9	−25.0	−26.8

very slight increase with depth to a maximum value of −25.5‰. In the upper 10 cm of the forest soil, the fractions coarser than 2 μm have $\delta^{13}C$ values ranging between −29 and −28‰, while the finest fractions are richer in ^{13}C, with values ranging between −26.6 and −26.1‰. With increasing depth, the difference between the $\delta^{13}C$ values of the coarsest and finest fractions increases to more than 4 units in the 30–40 cm layer.

The installation of pasture results in clear increases in $\delta^{13}C$ values in the topsoil particle-size fractions (Table 4). The greatest changes are observed in the upper layer, with differences ranging between 10.9 and 5.5 δ units in the coarsest and finest fractions, respectively. Only in the 30–40 cm layer, the $\delta^{13}C$ values are close to (0.2–2 μm fraction) or even more negative than (2–5 and 0–0.2 μm fractions) those of the corresponding fractions of the forest soil.

Percentages of C derived from forest and Pennisetum material

Whole soil

After ten years, the presence of C originating from the pasture (Cdp) is detected up to a depth of about 40 cm (Table 4), with a predominant input in the 0–20 cm layer (Table 5). In the upper 10 cm layer Cdp ranges between 8.4 and 9.5 t ha^{-1}, which represent from 46 to 52% of total C in this layer. In the 10–20 cm layer, Cdp drops to 2.7–3.0 t ha^{-1}, but still represents from 23 to 26% of the total C. When compared to the soil under native forest, the estimated value range of Cdf-losses in the whole 0–20 cm layer is 12.9–14.3 t ha^{-1}, that is 41–46% in ten years. It reaches 9.5–10.6 t ha^{-1} (47–55%) in the upper 0–10 cm layer, and does not exceed 3.4–3.7 t ha^{-1} (28–30%) in the 10–20 cm layer.

TABLE 5

Carbon contents (expressed in t ha^{-1}), percentages of C originated from forest (Cdf) and pasture (Cdp), and forest C losses (Cdf-loss) in the upper layers of the soils after ten years of pasture

Depth (cm)	Initial Ct (t ha^{-1})	Present Ct (t ha^{-1})	Cdp (%)	Cdp (t ha^{-1})	Cdf (%)	Cdf (t ha^{-1})	Cdf-loss (%)	Cdf-loss (t ha^{-1})
0–10[a]	19.2	18.2	52	9.5	48	8.7	55	10.5
			46	8.4	54	9.8	49	9.4
10–20[a]	12.2	11.5	26	3.0	74	8.5	30	3.7
			23	2.7	77	8.8	28	3.4
0–20[a]	31.4	29.7	42	12.5	58	17.2	46	14.2
			37	11.1	63	18.6	41	12.8

[a]Calculations were made using δ_p values of −13.0‰ (first line) and of −11.2‰ (second line).

TABLE 6

Carbon contents (expressed in mg g^{-1} of soil), and percentages of C derived from pasture (Cdp) in the particle-size fractions of the soil after ten years of pasture

Fraction (μm)	Unit	Depth (cm)			
		0–4	4–10	10–20	30–40
200–2000	mg C g^{-1} soil	5.82	1.75	0.49	0.18
	Cdp (%)[a]	61–68	43–47	38–43	31–35
50–200	mg C g^{-1} soil	6.71	3.65	1.32	0.28
	Cdp (%)	55–61	41–46	35–39	15–17
5–50	mg C g^{-1} soil	3.61	2.61	1.56	0.46
	Cdp (%)	47–53	36–40	27–31	4–5
2–5	mg C g^{-1} soil	1.81	1.76	0.85	0.94
	Cdp (%)	37–43	30–33	15–16	0
0.2–2	mg C g^{-1} soil	2.05	2.35	2.34	2.61
	Cdp (%)	34–39	32–36	17–19	4–5
0–0.2	mg C g^{-1} soil	0.70	0.42	0.33	0.33
	Cdp (%)	40–46	26–30	2–3	0

[a]Calculations were made using δ_p values of −13.0‰ and −11.2‰.

Particle-size fractions

The relative proportions of C deriving from the initial forest (Cdf) and from the pasture (Cdp) vary strongly with the size of the fractions (Table 6). In the surface layer (0–4 cm), inputs of Cdp are high in all fractions, and range from more than 50% in the coarse silt- and the sand-size fractions to 34–46% in the fine silt- and the clay-size fractions. Below 10 cm, the proportions of Cdp decrease with increasing depth. This decrease is relatively smooth in the sand- and coarse silt-size fractions, but is more abrupt in the fine silt- and clay-size fractions. In the deepest studied layer (30–40 cm), the proportion of Cdp is still between 31 and 35% in the coarse sand-size fraction, about

TABLE 7

^{14}C contents and radiocarbon ages in the main layers of the forest soil

Depth (cm)	$\delta^{14}C$‰	$\Delta^{14}C$‰	Apparent age (yr)	Corrected age (yr)
0–3	+107±7	+115±7	present	70±5
3–10	+105±8	+112±8	present	72±5
10–20	+11±8	+16±8	present	240±30
65–75	−268±8	−267±8	2576±91	
150–160	−455±11	−455±11	5013±171	

twice lower in the fine sand-size fraction, and not higher than a few percent units in the finest fractions.

Average ^{14}C dating of SOM

The radiocarbon activity $\Delta^{14}C$ measurements are positive in the upper 20 cm, due to the carbon of thermonuclear origin (Table 7). The activity decreases sharply with depth, especially between the humus rich (0–20 cm) layers and the subsoil. As a result, the corrected ages increase almost linearily, with an approximate slope of about 35 years cm^{-1}: in the 0–10 cm layer, the mean age of SOM is 70 years, and that determined in the 150–160 cm layer is about 5000 years.

DISCUSSION

Total soil organic carbon contents

The distribution of organic C with depth in the soil under native forest was characterized by a sharp decrease between 10 and 20 cm depth, as commonly observed in the humid tropics, especially in Brazilian soils (Volkoff and Cerri, 1988). According to Post et al. (1982) and Detwiller (1986), total C amounts close to or higher than 100 t ha^{-1} are frequent in the first meter of soils under tropical forest. The amount of 81 t ha^{-1} measured in the studied forest soil is rather low as compared with these data. This can be related in part to the sandy texture of the upper layers of these soils, since clayey soils developed on the same geological formation in the Amazon Basin were shown to be richer (Volkoff and Cerri, 1987; Choné et al., 1991).

The decrease in soil C content which was observed after ten years of pasture appeared to be relatively low, when compared with the results often reported about the effects of deforestation and installation of pastures in the tropics (Falesi and Veiga, 1986). This could be explained by the fact that this pasture had no longer been farmed for a few years, and that all plant residues produced during this period may have been incorporated to the soil, without losses by grazing or reaping. In a well-managed experimental farm of central Amazonia, Choné et al. (1991) also mentioned that the total C content of the initial forest soil had been recovered after 8 years of pasture. Although these results emphasize the capital influence of adequate management of cultivated pastures on SOM content and fate in the tropics, it has to be stressed that this kind of result was obtained on a limited number of samples, and might not be generalized. Besides, the quality of this newly formed SOM needs to be investigated, even though it seems to compensate the losses of SOM derived from the previous forest.

Distribution of carbon from forest and pasture origins

The accuracy of the calculation of Cdp, Cdf and Cdf-losses depends on several factors such as the ^{13}C labelling among soil components which is not uniform, and SOM mineralization, which can affect preferentially compounds or functional groups that are the poorest in ^{13}C isotope (Deines, 1980). Since the mechanisms of SOM mineralization are probably different in the two soils, the $\delta^{13}C$ values of forest C in the pasture soil can also differ from those in the forest soil, and from one site to another. As a matter of fact, $\delta^{13}C$ values of six topsoils developed in different regions of the Amazon forest, and under different climatic and litter decay conditions, were shown to range between −28.5 and −28.0‰ (Desjardins et al., 1991). In the case of neighbouring sites, it can reasonably be assumed that the $\delta^{13}C$ values of the forest C remaining in the pasture soil vary in the same narrow range of 0.5–1.0‰, as those of the forest topsoil. Il is also likely that the $\delta^{13}C$ values (δ_p) of organic residues derived from the pasture were not the same as those of the fresh material, as suggested by the 1.8‰ difference between leaves and roots. However, calculations using different values of δp showed that these variations did not affect strongly the results, especially in the finest fractions and deepest layers (Tables 5 and 6).

Even though the total C content in the pasture soil was only slightly modified, as compared to that of the forest soil, the strong changes in ^{13}C natural abundance were indicative of significant inputs and losses in C derived from the pasture and from the forest, respectively. In the 0–20 cm layer, the percentage (40–43%) of the initial forest C lost during the 10 year period was close to that (44%) measured after 8 years in a *Brachiaria* pasture of central Amazonia (Choné et al., 1991), even though in the latter situation, the total initial C content was about three times higher than that measured in the present case. Moreover, in central Amazonia the latter authors observed that this initial C content was quickly recovered, due to the inputs from the pasture. Conversely, in eastern Amazonia, the fact that the losses of initial forest C (12.7–13.4 t ha^{-1} in the 0–20 cm layer) were not completly compensated by

the inputs from the pasture (11.0–11,6 t ha^{-1}) could indicate that the surface humus had suffered a pronounced phase of degradation, as already observed under annual crops on the same location (Martins et al., 1991).

Another point of comparison can be taken in managed savannas of Ivory Coast, where Martin et al. (1990) have reported that 48% (14.5 t ha^{-1}) of the initial C were lost in the 0–25 cm layer, after 16 years of reforestation. These authors also noticed that the losses in C were imperfectly compensated by the input of 12.5 t ha^{-1} of C from the substituting vegetation. Although the situations in their study and the present one were rather different in terms of soil type, vegetation and duration of the alternative cover, the similarity between the two sets of results has to be pointed out. As a matter of fact, most of the existing results in the tropics indicate that about 10 years after the vegetation change, one half of SOM originating from the previous vegetation still remains in the surface soil layer.

Size distribution of carbon from forest and pasture sources

The grain-size fractionation of SOM showed clear differences between the two soils in the distribution of the total C: in the pasture soil, larger amounts of coarse organic residues were observed in the sand-size fractions of the upper layers, whereas less organic C was present in all other fractions of the whole profile, when compared with the forest soil (Table 3). These differences can be first attributed to a lower clay content in the pasture soil (Table 2), rather than to a lower C concentration of its 0.2–2 mm clay-size fraction. Although local texture variability cannot be totally discarded, it seems that changes in plant cover have resulted in a loss in clay-size SOM with respect to forest soils, as shown by Martins (1987) in the case of soils under annual crops of the same area. As SOM in the fine fractions is generally more humified than in the coarsest ones (Christensen, 1987; Feller et al., 1991), the results indicate that the installation of pasture resulted in the rejuvenation of the upper soil layer, through losses of Cdf and input of young Cdp. This loss of Cdf would therefore not be fully replaced by the inputs deriving from this secondary vegetation, especially in the fine fractions. Conversely, the relative accumulation of Cdp in the coarse fractions of the surface layers of the pasture soil could be due to a slowing down of the humification of this material, as a consequence of the waterlogging periods which were observed in the upper layers of the pasture soil.

Isotopic methods clearly confirmed that all size fractions were affected by losses of Cdf and by inputs of Cdp. As already observed in other locations (Vitorello et al., 1989), faster SOM turnover and substitution of Cdf by Cdp were observed in the coarse SOM fractions than in the fine ones. However, the differences observed in the present study between coarse and fine fractions were less pronounced, especially in the upper layer, than those found in other studies (Martin et al., 1990). This suggests that in the present case, the local conditions, i.e. the excess of water during the rain season, and the direct exposure to sunlight during the dry season, were less favourable to the decomposition of residues near the soil surface. It was also noticed that the differences between the inputs of Cdp in the coarse and fine fractions were increasingly pronounced with depth. These results confirm that (i) the clay-size fractions retain the C derived from the previous vegetation, more efficiently than do the coarser fractions, as already observed in earlier papers (Vitorello et al., 1989), and (ii) such a protective effect increases sharply with increasing depth, that is, with increasing age and/or humification time of SOM.

Distribution of carbon pools according to their age

In the forest soil, as in most of the soils (Scharpenseel, 1972; Guillet, 1979), the apparent ages of SOM calculated on the basis of the $\Delta^{14}C$ values, show an increasing gradient with depth. Such a gradient can be explained by a mixture of two SOM pools: one of recent and labile SOM, and one of old and stable SOM (Balesdent and Guillet, 1982). Since the homogeneity of the blending of SOM components along the soil profile increases with time, the oldest SOM pool is considered to be present at the same concentration in any layer of the soil profile. The mean age of the corresponding stable C pool is considered to be at least 5000 years, i.e. the apparent age measured at 150 cm depth (Table 7). In the two soils, C accumulated in the 0–100 cm layer reaches 80.7 and 76.8 t ha^{-1} under forest and pasture, respectively, whereas the amount of 2.8 mg g^{-1} in the 100–200 cm layer represents 42 t ha^{-1} (Desjardins, 1991). If this amount is regarded as the stable C pool, and is converted into t ha^{-1} in each horizon of the 0–100 cm soil layer, it would represent about 45.2 t ha^{-1}, that is about 59% of the total C. Since the age decreases almost linearily toward the soil surface, the proportion of the stable C pool also decreases with the increasing contribution of the labile C pool. Thus in the upper 20 cm layer, the stable pool would represent about 26% of the total C, and the labile one about 74%. Similarily, in the upper 10 cm layer, the calculation yields 16% and 84% for the stable and labile fractions, respectively.

These calculations were used, together with data from $\delta^{13}C$ measurements, to describe the distribution of Cdf and Cdp in the soil under *Pennisetum* pasture (Fig. 1). This figure suggests that after 10 years of pasture, a part only of the labile pool of Cdf has been degraded, since its proportion is still close to 50% in the first 0–20 cm layer. If situations of older and well managed pastures could be found in the same area, this calculation approach would allow (i) to confirm the existence of the stable forest pool, (ii) to establish whether the labile forest pool can disappear totally in case of vegetation change, and (iii) to forecast after how long time this disappearance is likely to occur.

In conclusion, this study has shown that although the total amount of soil

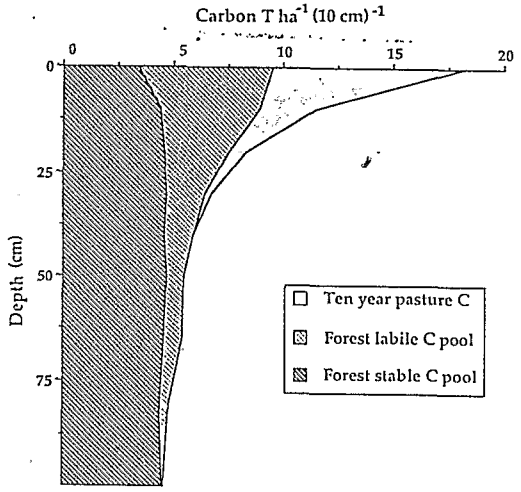

Fig. 1. Distribution of stable and labile C pools derived from forest, and of C derived from *Pennisetum*, in the soil after 10 years of pasture.

C seemed to have changed very slightly after ten years of pasture, the studied soil ecosystem of eastern Amazonia was highly fragile and sensitive to the plant cover substitution. Particle-size fractionation and ^{13}C natural abundance measurements have shown qualitative changes which were characteristic of a slowing down in humification processes. An accumulation of coarse organic fragments of graminaceous origin and a decrease in the amount of C associated with the fine fractions were observed. However in the present stage, and in the absence of sites under older pastures, these results do not allow to ascertain whether the system has already reached a new equilibrium or the observed loss in humus still corresponds to a decreasing phase.

AKNOWLEDGEMENTS

This work was partly supported by a grant from the French Ministère des Relations Extérieures, and by STD2-EEC project number TS22*0301-F(MSA). The conversion of samples into benzene for ^{14}C dating was performed at the Centre de Recherche Pétrographique et Géochimique of Vandœuvre (France). The authors whish to thank Mrs. M.J. Belgy and Mr. N. Suarta for their technical assistance in these determinations.

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GEODERMA

AN INTERNATIONAL JOURNAL OF SOIL SCIENCE

Geoderma, 61 (1994) 103–118
Elsevier Science B.V., Amsterdam

Organic carbon and ^{13}C contents in soils and soil size-fractions, and their changes due to deforestation and pasture installation in eastern Amazonia

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(Received May 6, 1992; accepted after revision April 5, 1993)

16 SEPT. 1994

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