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Soil properties under Amazon forest and changes due to pasture installation in Rondônia, Brazil

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Abstract

We examined the consequences of deforestation and pasture establishment for soil chemical and physical properties and for soil organic matter content, in Rondônia, in the southwestern part of the Brazilian Amazon basin. Two chronosequences were selected. One chronosequence consisted of a forest and pasture established in 1989, 1987, 1983, 1979 and 1972. The main soil type in this area is the red yellow podzolic latosol (Kandiudult). The second chronosequence consisted of a forest site and pasture established in 1987, 1983, 1972 and 1911, and the main soil type is a red yellow podzolic soil (Paleudult, Tropudult). The first soil type is the most base-depleted soil and has a higher clay content than the second one. Despite the initial differences in clay and cations contents between the forest sites the total soil carbon content at 0–30 cm in both forest were circa 3.7 kg C m^{-2}. After pasture installation soil bulk density were higher in the first 0–5 cm soil layer, mainly in one chronosequence but small changes were detected in deeper soil layers. Forest conversion to pasture caused appreciable increases in soil pH and exchangeable cation content, at least until nine years after pasture installation. pH levels were greater in the first chronosequence, with highest values (6.8 to 7.6) found in 3 and 5 years old pastures respectively. In the most base-depleted soil Ca content increased from 0.07 kg m^{-2} in the forest site to 0.25 kg m^{-2} in the 5 year old pasture. After normalization by clay content total soil carbon contents to 30 cm in the 20 year old pastures were 17 to 20% higher than in the original forest sites. Calculations of carbon derived from forest (Cdf) and from pasture (Cdp) using soil $\delta^{13}C$ values showed that Cdf decrease sharply in the first 9 years after pasture establishment in both chronosequences and reached stable values of 2.12 kg C m^{-2} and 2.02 kg C m^{-2} in chronosequences 1 and 2, respectively. Soil carbon derived from pasture increased with time and represented 50% of total

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soil carbon in the top 30 cm after 20 years of pasture. In general we observed that forest conversion to pasture is associated to a pattern of increasing of soil cations and pH levels for at least 5 years under pasture establishment. The removal of the original forest for pasture establishment resulted in an accumulation of carbon derived from pasture in the soil.

1. Introduction

The development of large agricultural programs of farming and cattle ranching in the Brazilian Amazon promoted by either official entities or private companies has hastened changes in regional land use. Myers (1991), estimated that agricultural expansion into tropical forest areas has been responsible for at least 50% of deforestation in the last two decades.

In the Brazilian Amazon, the most common land use consists of felling the large trees, removing economically important wood, and burning the remaining vegetation. The introduced agricultural practices include several forms of cropping: shifting cropping, intensive cropping or perennial plants, with or without pasture (Andreux and Cerri, 1989; Buschbacher et al., 1988).

Forest cutting and burning and pasture establishment leads to changes in soil organic matter and soil chemical and physical properties (Nye and Greenland, 1964; Diez et al., 1991a; Maggs and Hewett, 1993). Increases in soil pH and exchangeable cations and decreases in exchangeable acidity after forest cutting and burning have been reported by Ewel et al. (1981), Sanchez et al. (1982), Buschbacher et al. (1988) and Martins et al. (1991). Changes in nutrient content and soil physical properties have been associated with different cropping systems (Diez et al., 1991b) and intensive agriculture (Uhl, 1987).

It has been reported that deforestation affects soil carbon and nitrogen contents (Detwiller and Hall, 1988; Martins et al., 1991; Cerri et al., 1991; Veldkamp, 1994a) and increases CO_2 evolution to the atmosphere (Bolin, 1977; Houghton et al., 1983; Houghton, 1990). Recent studies in soil organic matter changes along forest to pasture sequence showed an increase in soil carbon content after an initial decline (Choné et al., 1991; Cerri and Andreux, 1990) near Manaus and in Rondônia (Moraes et al., 1995b). Although these studies do not presented detailed information on spatial variability of soil carbon data, it has been reported that the heterogeneity of the data is high, mainly under pasture (Veldkamp, 1994b).

In the present paper we describe changes in soil organic matter and soil physical and chemical properties related to forest clearing and pasture establishment in the southwestern Brazilian Amazon Basin. Two chronosequences with a forest site each and pastures of 3, 5, 9, 13, 20 and 81 years old were selected in a region with representative soils and land use type of the Brazilian Amazon basin. Pasture development is currently one of the major contributors to regional deforestation and represents the largest use of converted tropical forests (Serrão and Toledo, 1990; Fearnside, 1987), but controversy remains about the consequences on soil organic matter. The determination of losses of soil organic matter (SOM) from forest origin and of rate of its substitution by SOM from

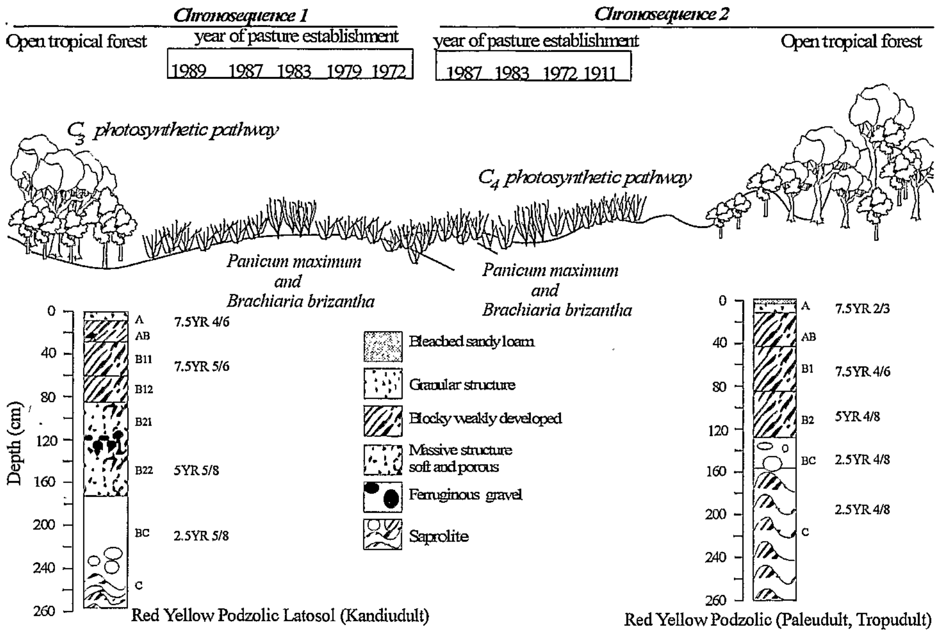

Fig. 1. Schematic representation of studied sites. In chronosequence 1 pastures established in 1989, 1987 and 1972 were dominated by *Brachiaria brizantha* and the other pastures were dominated by *Panicum maximum*. In chronosequence 2, pastures established in 1987 and 1911 were dominated by *Brachiaria brizantha* and those established in 1983 and 1972 were dominated by *Panicum maximum*.

pasture origin are important to understanding soil carbon and nitrogen cycles and patterns that control soil fertility.

2. Materials and methods

The forest-to-pasture sequences were located at Fazenda (Ranch) Nova Vida (10°10′05″S; 62°49′27″W), a 22,000 ha cattle ranch between the cities of Ariquemes and Jaru in Rondônia.

The climate of North Rondônia is humid tropical, Ami in the Köppen classification, with a short, but well defined dry season from June to August. The southern part of the State has a longer dry season and the climate is classified as Awi by Köppen (Bastos and Diniz, 1982). The mean annual rainfall at Porto Velho (northwest of Nova Vida Ranch) is 2270 mm. Further south, at Vilhena, annual rainfall is 2,086 mm. Mean annual maximum and minimum temperatures range from 24.4°C to 25.6°C and 18.8°C to 20.3°C respectively (Bastos and Diniz, 1982).

Two chronosequences were selected at Nova Vida. Chronosequence 1 consisted of a forest and pastures established in 1989, 1987, 1983, 1979 and 1972. Chronosequence 2 consisted of a forest and pastures established in 1987, 1983, 1972 and 1911 (Fig. 1). The native forest vegetation is open humid tropical forest with large numbers of palm-trees

(Pirez and Prance, 1986). Pastures in chronosequence 1 were dominated by *Brachiaria brizantha* (1989, 1987 and 1972) and *Panicum maximum* (1983 and 1979). Pastures in chronosequence 2 were dominated by *Brachiaria brizantha* (1987 and 1911) and *Panicum maximum* (1983 and 1972).

Pastures were created by felling the large trees with a chain saw, removing economically important wood and burning the remaining vegetation following the beginning of the rainy season in September. Pasture grasses were sown by airplane following burning. No mechanical agricultural practices or chemical fertilizers were used on any of the pastures.

At the time of the survey (July, 1992) approximately 10,000 to 15,000 cattle were on the ranch, with a mean stocking rate of 1 to 2 animals/ha. Pasture conditions differed with the youngest pastures (3 to 5 year old) containing a large number of palms and timber debris remaing from the forest.

Geomorphologically the Ranch area can be divided into two landscape patterns: (1) a sedimentary landscape of convex rolling hills with flat tops at about 200 m (Fig. 1) and (2) rocky hills with more irregular diameters and shapes because of a complex incision by a temporary river network. The altitude ranges between 130 and 170 m and the higher hills have a inselberg feature. Most hill flat tops have a thin lateritic like gravel mantle which probably results from the dismantling of a sedimentary rock composed of fine ferruginous sandstone occurring as a horizontal laminar layer.

Two main soil types were found in the area of the chronosequences. The soil in chronosequence 1 is a red yellow podzolic latosol (EMBRAPA, 1988) classified as Kandiudult in the U.S. Soil Taxonomy (Soil Survey Staff, 1990). This type of soil is also found in the pastures of chronosequence 2 in association with red yellow podzolic soil (EMBRAPA, 1988) or Ultisol (Paleudult, Tropudult). In the forest control site of chronosequence 2 the predominant soil is a red yellow podzolic soil. Both soils are representative soils of Amazon basin covering almost 60% of the Brazilian Amazon basin (Moraes et al., 1995a).

The red yellow podzolic latosol (Fig. 1) occurs on both the top position and the upper part of the slopes of the convex low hills. Below the leaf litter, the surface horizon is normally a very thin (10 cm) layer of bleached sand. The A horizon is a sandy clay loam, weakly structured about 10 cm thick. The AB horizon extends to 25 cm. The B1 horizon is brown or yellowish red, gradually becoming sandy clay . The structure is blocky and weakly developed. The underlying B2 horizon is yellowish red to red, soft, porous, and presents a sandy clay material with a massive structure. The lower part of this horizon may contain up to 50% of gravel and stones (from 2 to 20 cm in diameter) composed of flat ferruginous sandstone, subrounded ferruginous rock, and angular and subangular quartz. The average depth of this gravel and stone layer is 150 cm with an observed range of 50 cm to 250 cm. In the underlying BC, no more gravel is encountered but some fragments of weathered rock are observed. Clay content ranges from 20% (A-horizon) to 45% (B_2-horizon). The clay minerals consist of kaolinite and small amounts of gibbsite in both B and C horizons.

The Red Yellow Podzolic soil (Fig. 1) is typically associated with the rocky hill landscape. The surface A horizon is about 5 cm thick and brown, with a loamy sand texture. A thin, 1 cm sand layer is encountered on the top soil. The B2 horizon is yellowish red sandy clay loam or sandy clay and extends to more than 100 cm, with weak structural development. Saprolite is found at depths of 150 to 200 cm. From place to place, the soil texture of the B horizon changes, and its clay content ranging from 30% to 50%, which seems to be related to parent rock heterogeneity. The textural differentiation in the soil profiles remains clear in all situations. Kaolinite, mica and feldspaths are the mineralogical compounds of the clay fraction. In the upper part of the C horizon the mica content is very high. The amount of mica is less in the B2 horizon.

2.1. Sample collection and analysis

Soil samples were collected in each forest or pasture from a large pit ($80 \times 150 \times 150$ cm deep) and smaller ones ($40 \times 40 \times 50$ cm deep) in representative positions of the landscape. In the pit, soil was collected at 0–5, 5–10 cm and 10 cm layers thereafter until the bottom of the profile. Four additional samples were collected with an auger at 0–5, 5–10, 10–20 and 20–30 cm depths, 25 meters in each direction of the large pit. Soil samples of the smaller pits were collected as part of a European Economic Community Project (EEC, 1994) and were used to increase the number of repetitions. Morphological soil characteristics were described from the large pits and from fresh faces of soil profiles along the road cuts.

Laboratory analysis followed the methods of EMBRAPA (1979) and (Anderson and Ingram, 1989). Soil samples for pH, exchangeable cations and particle size fractions were homogenized, air-dried and sieved at 2 mm. Replicate soil samples were sieved through a 100 mesh (0.149 mm) screen for total carbon, nitrogen and carbon isotopic composition. Bulk density was determined from three replicate samples collected at each depth from the large pits using volumetric cylinders. Particle size fractions were determined by hydrometer after dispersion in a mixer with hexametaphosphate and digestion of organic matter with H_2O_2. Calcium, magnesium and potassium were extracted with ammonium acetate at pH 7. Calcium and magnesium were determined by atomic absorption spectrophotometry and potassium by flame emission spectrophotometry. Samples were analyzed for total carbon by dry combustion on a Carmograph 12A analyser. For total nitrogen samples were analysed by dry combustion on a Perkin–Elmer 2400 Elemental Analyser. The $^{13}C/^{12}C$ ratio was measured as CO_2 obtained by the complete combustion of the organic matter of a 100 mesh (0.149 mm) soil sample. The $^{13}C/^{12}C$ ratio was determined from triplicate subsamples on a Micromass 602 E mass spectrometer. The isotopic ratio was expressed in the δ per mil, in relation to the PDB standard and expressed in parts per mil according to the equation:

$$\delta^{13}C = \left(\frac{^{13}C/^{12}C \text{ sample}}{^{13}C/^{12}C \text{ standard}} - 1 \right) \times 1000 \qquad (1)$$

maximum absolute deviation was 0.3%

2.2. Clay and density corrections

For each soil layer (0–5, 5–10, 10–20 and 20–30 cm) we calculated the stocks of carbon, nitrogen and exchangeable cations by multiplying the concentration of the element (g g^{-1}) by ρ (kg m^{-3}) and layer thickness (m). The stock in the 0–30 cm layer was obtained by the sum of the above soil layers. The averages of Ca, Mg, K, C and N contents are presented in the text, followed by the respective standard deviation.

Changes in soil bulk density in pastures along chronosequences can cause errors when sampling is based on a fixed depth because deeper or shallower soil layers are sampled relative to the original forest Veldkamp (1994b). Then, we corrected soil C and N stocks to 30 cm based on sampling of a soil mass in the pastures that was equal to the mass to 30 cm depth in the original forest. This resulted in calculating C stocks based on a depth of slightly less than 30 cm when bulk density increased in pasture and slightly greater than 30 cm when bulk density decreased. We assumed that the C and N content of soil in the 20 to 30 $\pm x$ cm soil layer used to calculated stocks was equal to that in the sampled 20 to 30 cm layer.

For the present paper we attempted to account for small soil variations in clay content along the chronosequence by making the hypotheses that *for each soil type there is a close relationship between clay and carbon content and no changes in clay content occurs after pasture establishment*. Based on these assumptions, we normalized the carbon content inside each chronosequence by calculating the average clay content for each chronosequence for each soil layer and then adjusted the values for all the sites to the mean stocks per gram clay. This correction was based on the following equation:

$$\mathrm{C(corrected)} = \mathrm{C(measured)} \cdot \mathrm{Clay(reference)}/\mathrm{Clay} \qquad (2)$$

where Clay (reference) is a mean clay content for each soil layer, including the forest site.

It has been suggested that soil texture plays a role in determining the amount of organic matter in soil (Parton et al., 1987; Feller et al., 1991). Variation in soil carbon content is more closely related to the variation in soil texture than to others parameters like land-use changes and climate (Feller et al., 1991). Soil carbon variation is linear for those soils where clay content is lesser than fifty percent (Feller et al., 1991).

2.3. Estimate of carbon derived from C_3 and C_4 plants

The implantation of an another vegetation (grass — C_4 plants) with a different photosynthetic pathway from the original vegetation (forest — C_3 plants) provides a mechanism to trace the source of organic matter to the soil. Based on the variation of the $^{13}C/^{12}C$ ratio in soil, it is possible to quantify the amount of the total C (Ct) derived from forest (Cdf) and from pasture (Cdp) Cerri et al. (1985). In soils under pasture, organic C from forest (Cdf) and from pasture (Cdp) were expressed in kg C m^{-2} or as percent of total carbon (PCdf and PCdp) of the respective layer, using the following equations (Cerri and Andreux, 1990):

$$\mathrm{Cdp} = \mathrm{Ct} \times (\delta \mathrm{c} - \delta \mathrm{f})/(\delta \mathrm{p} - \delta \mathrm{f});\ \mathrm{Cdf} = \mathrm{Ct} - \mathrm{Cdp} \qquad (3)$$

$$\mathrm{PCdp} = 100 \times (\delta \mathrm{c} - \delta \mathrm{f})/(\delta \mathrm{p} - \delta \mathrm{f});\ \mathrm{PCdf} = 100 - \mathrm{PCdp} \qquad (4)$$

where Ct is the total carbon content of the pasture soil layer; δc is the $\delta^{13}C$ value of the respective soil pasture layer; δf is the $\delta^{13}C$ value of the corresponding forest soil layer and δp is the $\delta^{13}C$ value of selected *Brachiaria brizantha* or *Panicum maximum* litter material from each pasture. The δp were obtained from eight replicate samples for

Brachiaria brizantha with a mean value of -14.30 ± 0.56‰ and four replicate samples for *Panicum maximum* with a mean value of -15.49 ± 1.75‰.

2.4. Mathematical modelling

Two equations were used to determine the kinetics of decrease and accumulation of the two C sources. The choice of such equations is arbitrary and their adjustment to real field situation will greatly depend on the number of experimental sites that are controlled (Andreux et al., 1990). The exponential kinetics used take into account the hypothesis of a stable and biodegradable fraction of soil organic matter (SOM), and have been used by Jenkinson and Rayner (1977), Parton et al. (1987) and Andreux et al.

Table 1
Soil properties under natural forest and pasture in both chronosequences. Values following ± are standard deviations

Chronosequence 1				Chronosequence 2			
Land use	Bulk density (g/cm^3)	Clay (%)	pH (H_2O)	Land use	Bulk density (g/cm^3)	Clay (%)	pH (H_2O)
0-5 cm							
Forest	1.24±0.02	18.3	5.1±0.5	Forest	1.30±0.14	15.5	5.6±0.6
3 yr old pasture	1.31±0.09	18.5	6.8±1.1	5 yr old pasture	1.11±0.12	20.2	6.9±0.8
5 yr old pasture	1.32±0.03	25.9	7.6±0.5	9 yr old pasture	1.46±0.04	13.8	6.7 [a]
9 yr old pasture	1.56±0.04	19.6	6.1±0.2	20 yr old pasture	1.21±0.04	14.3	6.4±0.8
13 yr old pasture	1.41±0.04	20.3	6.1±0.1	81 yr old pasture	1.33±0.05	13.1	5.9±0.3
20 yr old pasture	1.30±0.11	22.3	5.7±0.4				
5-10 cm							
Forest	1.47±0.04	26.4	4.7±0.2	Forest	1.44±0.13	15.0	5.4±0.6
3 yr old pasture	1.47±0.08	28.9	6.4±1.0	5 yr old pasture	1.34±0.13	21.1	6.8±0.6
5 yr old pasture	1.48±0.03	31.6	7.2±0.3	9 yr old pasture	1.54±0.03	15.7	6.4
9 yr old pasture	1.59±0.05	28.8	6.1±0.3	20 yr old pasture	1.40±0.06	12.9	6.3±0.4
13 yr old pasture	1.43±0.04	24.2	6.1±0.3	81 yr old pasture	1.45±0.05	16.0	5.9±0.5
20 yr old pasture	1.44±0.03	23.7	5.7±0.3				
10-20 cm							
Forest	1.53±0.01	30.0	4.5±0.2	Forest	1.47±0.13	20.5	5.2±0.6
3 yr old pasture	1.49±0.01	33.9	5.8±0.9	5 yr old pasture	1.43±0.08	22.4	6.7±0.5
5 yr old pasture	1.44±0.02	34.6	6.9±0.3	9 yr old pasture	1.51±0.09	15.8	6.3
9 yr old pasture	1.57±0.04	31.6	6.3±0.3	20 yr old pasture	1.41±0.09	17.4	6.5±0.5
13 yr old pasture	1.47±0.04	28.1	6.2±0.3	81 yr old pasture	1.55±0.01	14.9	5.9±0.2
20 yr old pasture	1.45±0.13	28.5	5.7±0.3				
20-30 cm							
Forest	1.48±0.00	34.5	4.8±0.3	Forest	1.51±0.10	23.1	5.3±0.6
3 yr old pasture	1.43±0.05	38.2	5.5±0.7	5 yr old pasture	1.40±0.11	27.5	6.7±0.5
5 yr old pasture	1.47±0.01	38.3	6.6±0.7	9 yr old pasture	1.30±0.01	20.7	6.1
9 yr old pasture	1.48±0.02	36.9	6.4±0.3	20 yr old pasture	1.48±0.04	21.3	6.4±0.6
13 yr old pasture	1.47±0.01	30.5	6.2±0.4	81 yr old pasture	1.52±0.02	16.5	5.9±0.2
20 yr old pasture	1.52±0.06	35.2	5.5±0.4				

[a] Derived from one profile and no standard deviation calculated.

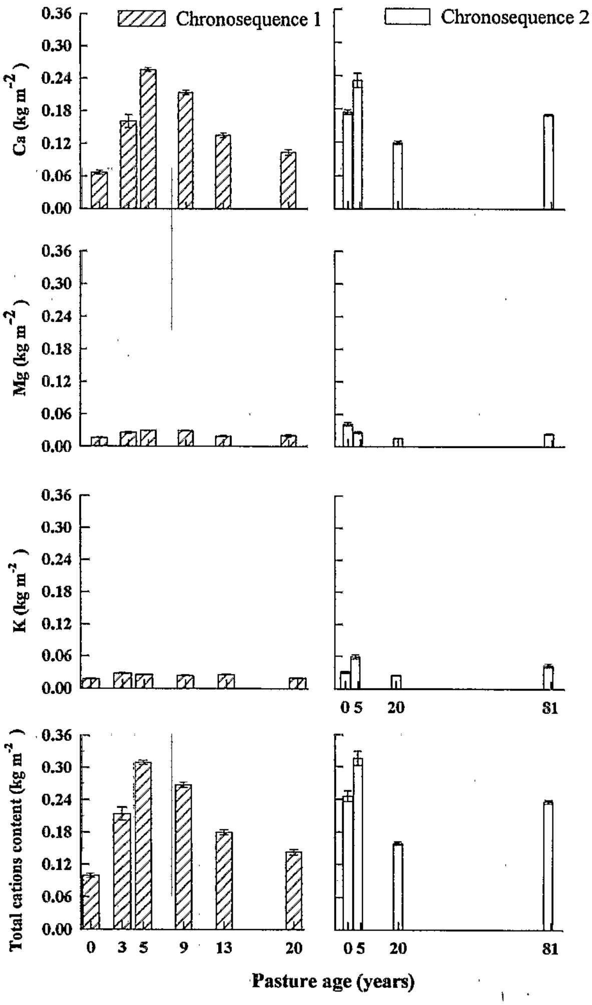

Fig. 2. Changes in soil cations contents (Ca, Mg, K) in the first 0–30 cm soil layer along chronosequences 1 and 2. In both chronosequences soil samples number for Ca, Mg and K ranged from three to nine. No samples were analyzed for Ca, Mg and K in the 8 year old pasture. Bars indicate the standard deviation.

(1990). According to Parton et al. (1987) the stable fraction is physically protected and chemically recalcitrant, with a large turnover time (150–200 years). Otherwise, the biodegradable fraction, that correspond to the active pool of SOM, consist of plant residues, live microbes, microbial products, with a short turnover time (1–5 years). The equations are:

$$\mathrm{Cdf} = \mathrm{Cdfs} + \mathrm{Cdfb} \times [\exp(-k_f \cdot t)] \tag{5}$$

$$\mathrm{Cdp} = \mathrm{Cdp}\infty \times [1 - \exp(-k_p \cdot t)] \tag{6}$$

where Cdf = amount of organic C from forest; Cdp = amount of C from pasture; Cdfs = stable fraction of initial amount of Cdf; Cdfb = biodegradable fraction of initial amount of Cdf; Cdp∞ = maximum net gain of Cdp; k_f^{-1} and k_c^{-1} = respective mean residence time (MRT) of the C sources (Andreux et al., 1990). The estimates parameters of each equation is presented followed by their respective standard errors.

3. Results

The 81 year old pasture reported in this paper as an example of long term changes on soil properties due to deforestation and pasture establishment is not representative of the land use types in the Brazilian Amazon basin. Because of this the major results and

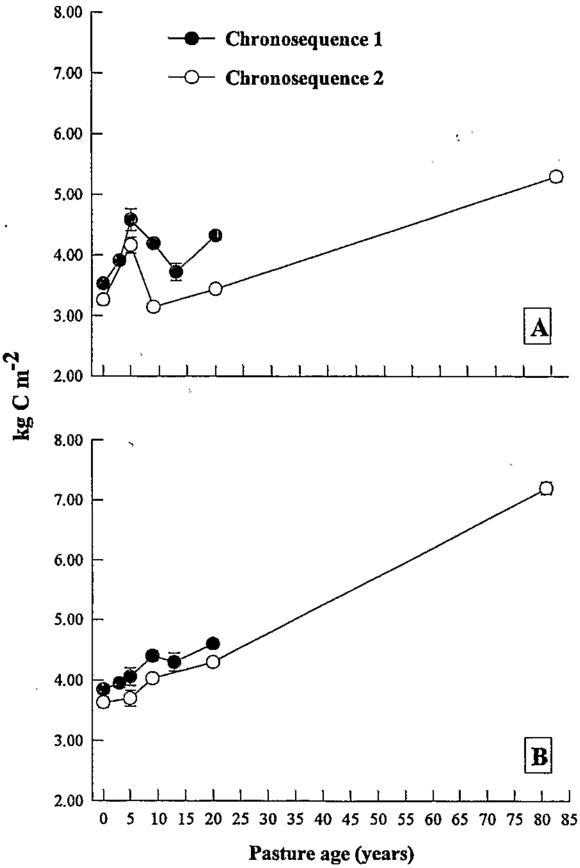

Fig. 3. Evolution of the C content in the 0–30 cm layer after pasture installation, taking into account the variations in soil bulk density (A). The same data, after normalization for the mean clay content, with the assumption that C is proportional to the clay content (B). For chronosequence 1 we had six repetitions in the forest site, eleven in the youngest pasture, five repetition in the 5, 9 and 13 year old pasture and nine repetitions in the 20 year old pasture. For chronosequence 2 we had thirteen repetitions in the forest site, six in the youngest pasture, five in the 20 and 81 year old pasture and just one repetition in the nine year old pasture. Bars indicate the standard deviation.

discussion presented are related to the forest to 20 year old pastures from both chronosequences.

The bulk density of forest soils in the surface 0–5 cm soil layer ranged from 1.24 to 1.53 g cm^{-3} in chronosequence 1 and from 1.30 to 1.51 g cm^{-3} in chronosequence 2. The use of soil with pasture resulted in an increase of soil bulk density in the surface 0–5 cm layer in chronosequence 1, but small changes were observed in deeper layers in both chronosequences (Table 1).

Both chronosequences present soils with clear textural differentiation in deep layers (Table 1). Clay content variation between forest sites was small (18.3% in chronosequence 1 and 15.5% in chronosequence 2) in the first 0–5 cm, but becomes greater in deeper layers. Soil from pastures in both chronosequences showed an increment in clay content down the profile and a high sand content in the first 0–10 cm layer. Along chronosequences, differences in clay content were not clearly related to pasture age.

The soil pH (H_2O) differed between forest sites from both chronosequences, with lower values in chronosequence 1 (Table 1). Changes in soil pH were greater in chronosequence 1, where highest pH levels were 6.8 in 3 year old pasture and 7.6 in 5 year old pasture. The same pattern was observed in chronosequence 2, but there was less changes considering the initial pH level of the forest site.

Exchangeable cations content were different between forest sites. At forest site from chronosequence 1, in the first 0–30 cm, Ca content was about 0.07 kg m^{-2} and 0.17 kg m^{-2} in chronosequence 2 (Fig. 2). The same trend was observed, however with lower difference, for Mg and K. In chronosequence 1, where forest soil had a lower cation content, an increase in exchangeable cations was clearly observed, between 3 and 9 year old pastures. Changes in Ca content were greater than those observed with Mg and K. K in soils under pasture remained higher than in soils under forests in both chronose-

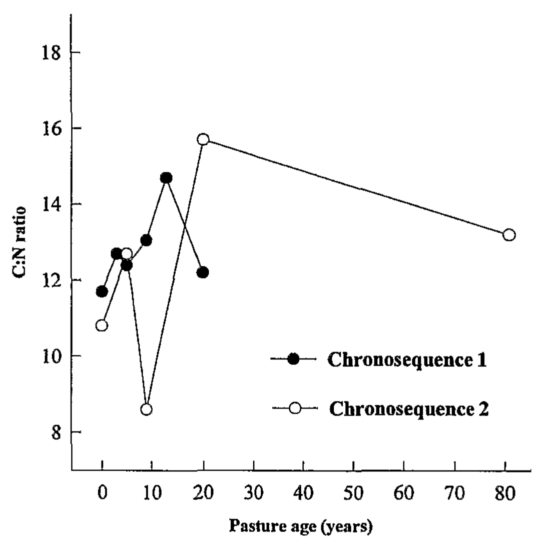

Fig. 4. Mass C:N ratios of the 0–30 cm soil layer under forest and pasture sites.

quences, except for 20 year old pasture in chronosequence 2. In the red yellow podzolic latosol , the total content of Ca, Mg and K in soils under pasture remained higher than in the forest soil because of the increase of each cation. In the red yellow podzolic we found an initial increase under 5 year old pasture, followed by a reduction in the 20 year old pasture.

3.1. Carbon and nitrogen contents

Carbon content to 30 cm was 3.50 ± 0.06 kg C m^{-2} and 3.30 ± 0.08 kg C m^{-2} respectively in both forest sites from the chronosequences (Fig. 3A). In pasture areas the

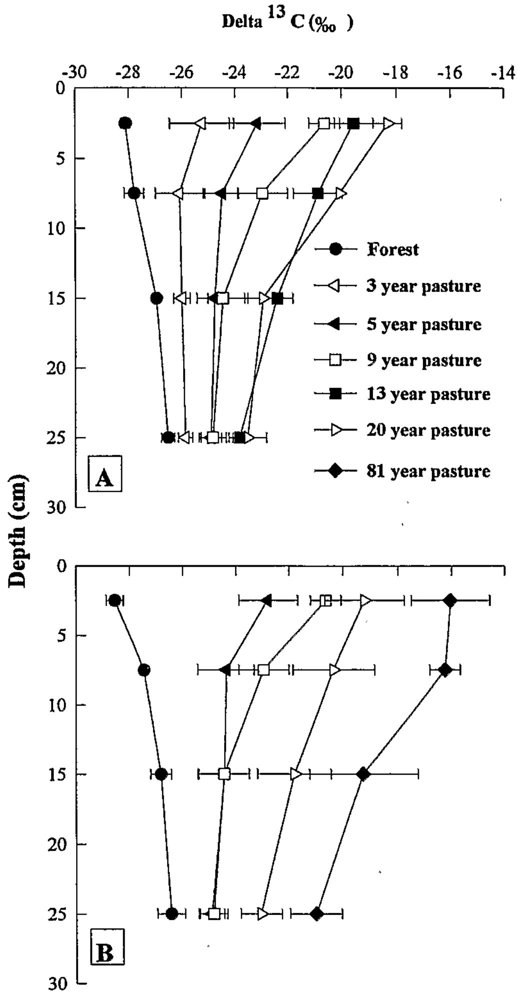

Fig. 5. $\delta^{13}C$ distribution in soils profiles from forest and pasture sites in chronosequence 1 (A) and chronosequence 2 (B) with the respective standard deviations.

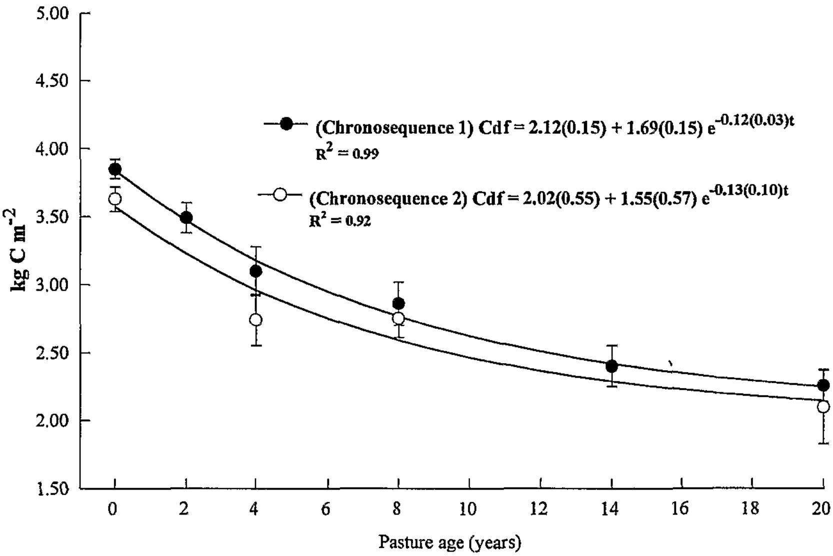

Fig. 6. Organic carbon derived from forest (Cdf) in the top 30 cm layer in chronosequences 1 and 2. Bars indicate standard deviation and numbers in brackets are standard errors.

carbon content were higher in relation to the forest site in both chronosequences with a maximum of 4.60 ± 0.18 kg C m^{-2} under 5 year old pasture of the first chronosequence and 5.30 ± 0.08 kg C m^{-2} under 81 year old pasture of the second chronosequence. After the correction for clay content the carbon content increased uniformly along the chronosequences with a maximum of about 4.5 kg C m^{-2} under 20 years old pastures of both chronosequences (Fig. 3B). In the sandy loam soil of the second chronosequence the carbon content remained lower than the observed stocks in the first chronosequence were soil clay content is higher. In the reference 81 year old pasture the carbon content was 5.3 ± 0.08 kg C m^{-2}. With correction for clay, the calculated stocks was 7.2 ± 0.10 kg C m^{-2} (Fig. 3B).

Nitrogen contents did not presented the same pattern of increasing along both chronosequences as observed for carbon. Both forest sites presented basic the same nitrogen content (0.33 kg N m^{-2}). After pasture establishement the stocks of this element ranged between 2.99 kg N m^{-2} to 3.80 kg N m^{-2} in the first chronosequence and between 2.74 kg N m^{-2} to 4.50 kg N m^{-2} in the second chronosequence. Except for the eight year old pasture of the second chronosequence, the mass C:N ratio were higher in the surface soils of other pastures compared with the original forest (Fig. 4). The C:N ratios were generally in the range of 8 to 16. The higher C:N ratios in the pastures is consistent with the relatively greater accumulation of C relative to N in the older pastures.

3.2. Variations of $\delta^{13}C$ in soil profile

The $\delta^{13}C$ isotopic composition in both forest sites ranged from −28.0‰ and −28.5‰ in the surface 0–5 cm to about −26.5‰ in deeper layers from chronosequence 1 and 2, respectively (Fig. 5). The introduction of C_4 grass vegetation, which has a different ^{13}C discrimination than the original C_3 forest vegetation, provides the source of all soil organic matter enriched in ^{13}C. The increase in $\delta^{13}C$ values is associated with increasing in pasture age and is strongest in the 0–10 cm layer. In the 81 year old pasture, the $\delta^{13}C$ values in the 0–10 cm layer, was very close to the grass $\delta^{13}C$ value of $-14.27‰$.

3.3. Soil organic matter dynamics

The organic C derived from forest (Cdf) decreased along the time (Fig. 6). In the upper 30 cm layer of the pasture soil, the stable carbon pool was about 2.12 ± 0.15 kg C

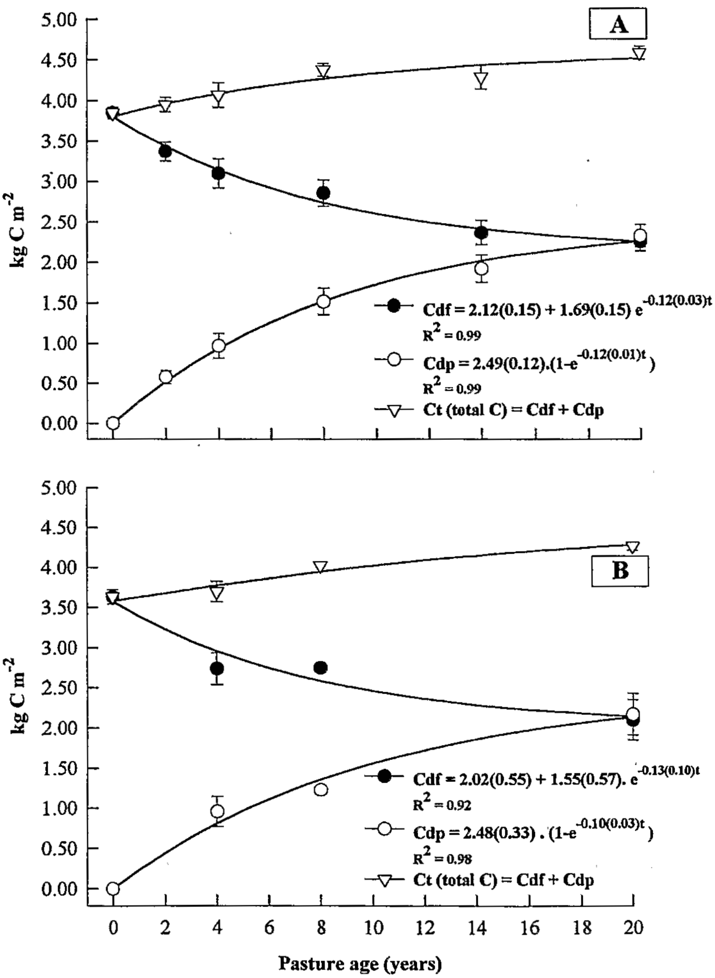

Fig. 7. The dynamics of total soil carbon (Ct), carbon derived from forest (Cdf) and carbon derived from pasture vegetation (Cdp) in the top 0–30 cm soil layer in chronosequence 1 (A) and 2 (B). Bars indicate standard deviation and numbers in brackets are standard errors.

m^{-2} in chronosequence 1 and 2.02 ± 0.55 kg C m^{-2} in chronosequence 2, while the biodegradable C pool was 1.69 ± 0.15 and 1.55 ± 0.57 kg C m^{-2} in chronosequences 1 and 2 respectively. Small differences were observed in the stable and biodegradable carbon pools when the 81 year old pasture was included in the model. The mean residence time (MRT) of Cdf was about 8 years in both chronosequences.

Total soil C increased with pasture age (Fig. 7A, B) but after 20 years of pasture the remaining Cdf still comprised 49% of the total soil C in both chronosequences. The increase in carbon derived from pasture (Cdp) showed a very similar pattern in both chronosequences with a maximum net gain ($Cdp\infty$) of 2.49 ± 0.12 kg C m^{-2} in chronosequence 1 and 2.48 ± 0.33 kg C m^{-2} in chronosequence 2.

4. Discussion

4.1. Soil physical and chemical properties

Although soil morphological characteristics were similar among all sites within each chronosequence, we observed an increase in soil bulk density in soils under pasture, mainly in the surface 0–5 cm layer in chronosequence 1. Changes in soil bulk density in pastures created on converted tropical forest soils were smaller than those observed by other studies (Buschbacher et al., 1988; Luizão et al., 1992; Martins et al., 1990, 1991). Moraes et al. (1995b) in two other chronosequences studied in the same region, found both increase in soil bulk density in one chronosequence and a decrease in the other, after pasture installation.

Soil pH can be strongly affected by forest burning through effect of a large amount of ash from the aboveground forest biomass burned (Nye and Greenland, 1964; Ewel et al., 1981; Bonde et al., 1992). Increase in soil pH was more significant in the 0–5 cm soil layer and in the youngest pastures. After the initial increase through 5 year old pasture, soil pH tend to decrease as a consequence of reduction in exchangeable cations, but still remained higher than the pH values from the forest sites. The higher pH in the 20–30 cm layer of the soil under 5 year old pasture suggests both a pedogenic and nutrient leaching effects.

Forest burning releases nutrients in the ash that raises pH values (Andreux and Cerri, 1989). Sanchez et al. (1983) reported that the ash from the burning of a Peruvian forest produced a temporary increase in K, Ca and Mg levels and some micronutrients. Increase in K that we observed could confirm the benefits of the ash in supplying this nutrient to the soil. Brinkmann and Nascimento (1973), found that the K of standing crop that returned to the forest floor as annual litter is in order of 12 kg K ha^{-1} $year^{-1}$. Ewel et al. (1981) reported that after forest was felled and burned on Costa Rica, the ash contained approximately 2.8% of K, and accounted for one half of the postburn K of the soil.

Changes in soil cation content after pasture installation in chronosequence 2, were smaller than those observed in chronosequence 1. Comparing the cation content from both forest sites, we found that the red yellow podzolic soil from chronosequence 2 had an initial cation content higher than the more leached red yellow podzolic latosol from chronosequence 1. In the 20 year old pastures, the total amounts of Ca + Mg + K were quite the same in the both chronosequences.

According to Sanchez et al. (1983), the extent of burning, either of the original forest or of the pasture after pasture installation to control weeds is the main contributor to site variability beyond the original pre-clearing differences. In the two chronosequences, the changes related to the age seems to be greater than the variability introduced by such spatial heterogeneity in the burning. The similarity observed in 20 year old pastures means that the original pre-clearing differences were obliterated despite of the clear differences in the clay contents of the upper soil . It can indicates the probably more important contribution of the organic matter than of the clay mineral fraction, specially clay of low cation exchange, for the nutrient retention in these soils under old pasture.

4.2. Soil C and N contents

The chronosequences we studied showed both short and long term changes in soil organic matter content due to forest cutting and pasture development. Changes in land use in the Amazon basin has been associated with a decrease in soil carbon stocks, with the magnitude of the decrease depending on the type of land use established after forest cutting (Allen, 1985; Mann, 1986 and Detwiller and Hall, 1988).

Our results showed an increase of 19% and 17% in total soil carbon (corrected by density and clay content) after 20 years of pasture installation in chronosequences 1 and 2 respectively (Fig. 3B). Without correction by clay content (Fig. 3A), the observed increase in total soil carbon content was 22% and 5% respectively. Studies carried out in the same region in Rondônia in another chronosequences reported an increase in total soil C in one chronosequence (on Oxisol) and no significative changes in another (on Ultisol with sandy top soil), in 20 year old pasture (Moraes et al., 1995b). The same trend was observed by Choné et al. (1991), showing a recovering of the initial carbon content of the forest after 8 years of pasture installation in a clayey (70% of clay) Oxisol of Manaus region, after a decrease after initial burning. In all situations, pastures were not subjected to extremes of burning regimes or overgrazing.

In a geostatiscal survey developed in the forest and pasture sites of the study area, Grzebyk (personal communication) found a total carbon content, without clay correction, of 3.11 ± 0.10 kg C m^{-2} in the first 0–30 cm soil layer in forest area of chronosequence 2, based on 193 replicate samples. This value is very close to the 3.3 ± 0.08 kg C m^{-2} that we found. In the pastures areas, Grzebyk, observed a decrease of 5% in carbon content in 3 year old pasture (87), followed by increase of 5% and 10% after 9 and 20 year of pasture, based on 87, 143 and 18 replicate samples respectively.

In contrast to our results, Veldkamp (1994a) reported a net soil organic carbon loss of 2 to 18% after 25 years of native pasture (*Axonopus compressus*) in the Atlantic zone of Costa Rica. Therefore Veldkamp (1994c) reported that the belowground net primary production is a major source of organic carbon in soils cultivated with pasture. The input of carbon is estimated to range from 40 to 85% of total net primary production and is about twice high for the improved species of *Brachiaria* compared to the native species *Axonopus* (Veldkamp, 1994c). This potential of introduced pasture in sequestering C was reported by Fisher et al. (1994) in an oxisol of the eastern plains of Colombia where areas cultivated with pastures showed considerable accumulation of carbon mainly in deeper layers (10–20 cm) less vulnerable to oxidation and loss. This results agree with the accumulation in C content in the first 0–30 cm layer observed in this study mainly in older pastures.

Total soil N content did not show the same pattern of increase as observed for carbon. Variation in nitrification and mineralization rates are strongly related to patterns of land use changes and could influence the total nitrogen pools (Piccolo et al., 1994). In Pará, Buschbacher et al. (1988) found no clear relationship between soil N content and pasture age, but soil N content were lower in intensively used 8 year old pasture compared with more lightly used pastures.

4.3. Soil organic matter dynamics under forest and pasture

The $\delta^{13}C$ values in our forest profiles showed a variation of 1.5‰ in the top 30 cm soil layer in chronosequence 1 and 2‰ in chronosequence 2 (Fig. 5). It is now well established that the $\delta^{13}C$ values of SOM increase between 1 and 2‰ from the surface to median horizon (50 cm) in profiles of intertropical forest (O'Brien and Stout, 1978; Volkoff and Cerri, 1987; Schwartz, 1991; Desjardins et al., 1991; Balesdent, 1991). O'Brien and Stout (1978) reported that increase of $\delta^{13}C$ in soil profiles is closely related to SOM mineralization, or the presence of old organic matter in deep layers. According to Balesdent (1991), differential humification in forest soil profiles, atmospheric variation of CO_2 concentration and changes in the vegetation and its environment (except changes from C_3 to C_4 vegetation), are the main factors that influence the $\delta^{13}C$ from forest soil organic matter. As expected, we observed an increase in $\delta^{13}C$ of soil when the C_3 forest vegetation was replaced by C_4 grassland vegetation.

The kinetics of soil organic matter showed that forest derived carbon declines sharply in the first years of pasture installation in both chronosequences and reached a very similar value of 2.12 ± 0.15 and 2.02 ± 0.55 kg C m^{-2} in chronosequences 1 and 2, respectively (Fig. 6). Both chronosequences presented the same rate of decline of the biodegradable carbon fraction (Cdfb), with ninety nine percent of degradation after 36 years of pasture establishment. Our findings differ from the four years estimated by Cerri and Andreux (1990) for 99% of the Cdfb to be degraded in a forest to pasture sequence in a clayey asocial near Manaus in the Central Amazon. This difference could be explained by the inexisting dry season and higher precipitation around Manaus.

5. Conclusion

The Amazon basin consists of a large diversity of land use types. Even considering that pastures are the largest land use type, the viability of this land use as a sustainable practice and its effects on soil nutrients and soils organic matter require a better understanding of soil carbon dynamics. Pastures represent an alternative land use in the Amazon basin, but their success is likely to be closely related to good pasture management and initial forest soil fertility.

Our findings have shows that forest conversion to pasture was associated with a general pattern of increasing soil cations and pH, for at least 5 years of pasture establishment followed by a decrease in subsequent years. Although, these soil chemical properties remained at higher levels in 20 year old pasture than in the original forest sites.

Soil carbon content presented small differences under natural forest but the removal of the original vegetation for pasture establishment was associated with significant changes in soil organic matter that resulted in an increase in soil carbon content. The mathematical modelling of soil organic matter dynamics provided important data about the turnover rate of the soil organic matter on areas converted to pasture. This kind of information will be useful for future studies of total carbon fluxes resulting from land use change in the Amazon basin.

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Volcanic Ash Soils

Genesis, Properties and Utilization

by **S. Shoji, M. Nanzyo** *and* **R.A. Dahlgren**

Developments in Soil Science Volume 21

Volcanic eruptions are generally viewed as agents of destruction, yet they provide the parent materials from which some of the most productive soils in the world are formed. The high productivity results from a combination of unique physical, chemical and mineralogical properties. The importance and uniqueness of volcanic ash soils are exemplified by the recent establishment of the Andisol soil order in Soil Taxonomy. This book provides the first comprehensive synthesis of all aspects of volcanic ash soils in a single volume. It contains in-depth coverage of important topics including terminology, morphology, genesis, classification, mineralogy, chemistry, physical properties, productivity and utilization. A wealth of data (37 tables, 81 figures, and Appendix) mainly from the Tohoku University Andisol Data Base is used to illustrate major concepts. Twelve color plates provide a valuable visual-aid and complement the text description of the world-wide distribution for volcanic ash soils. This volume will serve as a valuable reference for soil scientists, plant scientists, ecologists and geochemists interested in biogeochemical processes occurring in soils derived form volcanic ejecta.

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