Soil carbon and nitrogen stocks following forest conversion to pasture in the Western Brazilian Amazon Basin

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ABSTRACT. We examined two chronosequences of forest, 8-and 20-year-old pasture in Rondônia-Brazil, to investigate how land use change affects the soil carbon and nitrogen stocks and organic matter dynamics of surface soil (0 to 30 cm). Soil total carbon and nitrogen stocks increased in 20-year-old pasture compared with the original forest in one chronosequence but no changes were detected in the other chronosequence. Calculations of the contributions of forest - and pasture-derived carbon from soil $\delta^{13}C$ values showed a general pattern of pasture carbon augmenting a slowly declining pool of carbon derived from the original forest. Soil $\delta^{13}C$ values at 0 to 10 cm increased from -27 to -28 $\%_{oo}$ in the forests to approximately -20 $\%_{oo}$ in the 20-year-old pastures and reflected greater inputs of pasture-derived C_4 carbon in older pastures. If typical of larger areas of pasture in the Amazon Basin, these changes in soil carbon and nitrogen stocks following forest conversion to pasture have important implications for understanding the global biogeochemical cycles

Key words: Amazon, soil organic matter, tropical forest, tropical pasture

RESUMO. Estoques de carbono e nitrogênio no solo na seqüência floresta-pastagem na região oeste da bacia amazônica brasileira. Avaliou-se o impacto do desmatamento e implantação de pastagens nos estoques de carbono e nitrogênio e na dinâmica da matéria orgânica do solo, em duas cronossequências com florestas e pastagens de 8 e 20 anos em Rondônia. Os conteúdos de carbono e nitrogênio aumentaram na pastagem com 20 anos de implantanção em uma das cronossequências estudadas, mas poucas alterações foram observadas na outra cronossequência. O uso de $\delta^{13}C$ permitiu diferenciar e quantificar as duas fontes de carbono no solo sob pastagem, ou seja, o carbono remanescente da floresta e o introduzido pela pastagem. Verificou-se uma tendência de aumento do carbono do solo derivado da pastagem, acompanhado de um declínio do carbono do solo derivado da floresta. Os valores de $\delta^{13}C$ do solo na camada de 0-10 cm variaram de -27 $\%_{oo}$ a -28 $\%_{oo}$ na floresta para aproximadamente -20 $\%_{oo}$ na pastagem com vinte anos de implantação, o que confirma a entrada de uma grande quantidade de carbono no solo derivado de plantas C_4. As mudanças verificadas nos estoques de carbono e nitrogênio do solo, em áreas de sucessão floresta-pastagem, possuem implicações importantes nas análises dos ciclos biogeoquímicos globais.

Palavras-chave: Amazônia, matéria orgânica, floresta tropical, pastagem

Introduction

Large areas of the humid tropics are undergoing rapid conversion from forest to pasture. Estimates indicate that forest clearing rates in the American tropics now fall in the range of 11,000 to 15,000 km^2 yr^{-1} (Skole and Tucker, 1993; Fearnside, 1993), with Brazil accounting for 36 to 48% of the total (Myers, 1991). In the Brazilian Amazon Basin, pasture represents the largest use of converted tropical forests (Fearnside, 1987). Pasture creation has important effects on soil physical and chemical characteristics and the role of soils in long-term storage of carbon (C) and nitrogen (N). A better understanding of these changes is important for predicting the effects of land use change on soil fertility and consequences for the global carbon cycle (Detwiler and Hall, 1988; Houghton *et al.*, 1991).

The rate of loss of soil organic matter derived from forest vegetation and the rate at which it is replaced or augmented by soil organic matter derived from pasture grasses are important for understanding soil C and N cycles and patterns that control soil fertility. The sources and fates of organic matter after tropical forest conversion have been traced using $\delta^{13}C$ based on the change from C_3 forest vegetation to C_4 row crops or pasture grasses. These studies indicate that a substantial fraction of the soil C derived from the original forest vegetation remains in soils even after 20 to 50 years (Choné *et al.*, 1991; Bonde *et al.*, 1992a; Moraes *et al.*, 1996; Neill *et al.*, 1997; Bernoux *et al.*, 1998). Organic matter quality is also important in controlling rates of C and mineral nutrient cycles in forest soils. The conversion of forest to pasture may lead to substantial changes in soil organic matter quality as C derived from pasture grasses replaces that derived from the original forest vegetation, because grasses contain a lower concentration of lignin than woody vegetation (Parton *et al.*, 1987).

In this study, we describe changes in soil C and N stocks and the sources and quality of soil organic matter following forest clearing and pasture establishment in Ouro Preto, Rondônia, an area of very active forest clearing and relatively productive pastures in the western Brazilian Amazon Basin.

Material and methods

Two chronosequences were located with the help of local farmers at two locations in the Município of Ouro Preto do Oeste (10°44' 30" S, 62° 13' 30" W) along BR-364 in central Rondônia. Chronosequence I was located at Fazenda (Ranch) Benjamin approximately 4 km west-northwest from Ouro Preto on Line Road 4 and consisted of a forest tract and pastures of 8 and 20 years old. Chronosequence II was located at Fazenda Lenk, 18 km northwest from the town of Ouro Preto and 3 km from the junction of Line Roads 63 and 4 and also contained a forest tract and 8- and 20-year-old pastures. Soils of chronosequence I were Argissolo Vermelho Amarelo (Embrapa, 1999) or Tropudult (Soil Taxonomy, 1996) in the forest and Latossolo Vermelho Amarelo Argissólico (Embrapa, 1999) or Haplorthox (Soil Taxonomy, 1996) in the 8- and 20-year-old pastures. Soils of chronosequence II were classified as Argissolo Vemelho (Embrapa, 1999) or Tropudalf (Soil Taxonomy, 1996) in the forest and Latossolo Vermelho Amarelo (Embrapa, 1999) or Eutrorthox (Soil Taxonomy, 1996) in the 8 and 20-year-old pastures. These soils are representative of Amazon basin covering almost 60% of the Brazilian Amazon basin (Moraes *et al.*, 1995).

The forests in both chronosequences were typical of the open, humid tropical forests with large numbers of palms that dominate most of Rondônia (Pires and Prance, 1986). In chronosequence I, the 8-year-old pasture contained "colonião" (*Panicum maximum*, Jacq.) and the 20-year-old pasture was vegetated by a combination of "brachiarão" (*Brachiaria brizantha*, [Hochst] Stapf.) and "braquiária" (*Brachiaria decumbens*, Stapf.) (Table 1). In chronosequence II, the 8-year-old pasture contained "colonião" and the 20-year-old pasture contained "brachiarão" (Table 1). Neither mechanized agricultural practices nor chemical fertilizers were used on any of the pastures.

Sample collection and analysis

Soil samples were collected from 0 to 10 cm, 10 to 20 cm and 20 to 30 cm depths. Four samples were collected from each site along the chronosequence. One sample consisted of approximately 2 kg collected from the wall of a soil pit (0.8 x 1.5 x 1.5 m deep). Three additional replicate samples were collected from pits located 50 m in a line from the first pit. For these replicates, one entire m^2 of soil was collected for 0 to 10 cm, 10 to 20 cm and 20 to 30 cm layers. These samples were prepared by passing them through a 2 mm sieve, then grinding and passing them through a 0.25 mm (100 mesh) screen. For descriptive purposes, samples from the large pit were analyzed for particle size and pH. Samples from the three replicate samples were analyzed for total C, total N and $\delta^{13}C$. Bulk density at each depth was determined from 4 replicate volumetric cylinders collected from each face of the deep soil pit and dried at 105 °C.

Particle size fractions were determined by hydrometer after dispersion with hexametaphosphate and digestion of organic matter with H_2O_2. Soil pH was measured in water (1:2.5). Total C was analyzed by dry combustion on a Whösthof-Carmograph 12A. Total N was measured on a Perkin Elmer 2400 Elemental Analyzer. Lignin and cellulose fractions and lignocellulose index (ratio of lignin to total lignin+cellulose) were determined on duplicate subsamples from the soil sample from the deep pit at each site along the chronosequence, using sequential extractions with dichloromethane, water and sulfuric acid according to a method modified from the Technical Association of the Pulp and Paper Industry (Ryan *et al.*, 1990). Soil $^{13}C/^{12}C$ ratio was determined on triplicate subsamples from each of the 3 replicate samples at each depth using a Micromass 602 E mass spectrometer. The ratio of $^{13}C/^{12}C$ of the sample was expressed in δ values in parts per mil

relative to the Peedee Belemnite standard, according to the formula:

$$\delta^{13}C = [(R_{sample}/R_{standard}) - 1] \star 10^3; R = {}^{13}C/{}^{12}C \qquad (1)$$

Changes in bulk density in pastures along the chronosequence 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, 1993). 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 calculate stocks was equal to that in the sampled 20 to 30 cm layer.

Errors associated with C and N stocks were determined from the variances associated with bulk density and percent C or N at each depth as follows:

$$s^2_{C \star D} = s^2_C \star s^2_D + x^2_C \star s^2_D + x^2_D \star s^2_C \qquad (2)$$

where s^2_C and s^2_D are the variances of percent C and density and x_C and x_D are the mean percent C and density.

Relative contributions of forest and pasture-derived soil C were calculated for each soil layer as a simple linear mixture of forest (C_3) carbon and pasture (C_4) carbon, according to the equation:

$$C_s \star \delta^{13}c_s = (C_f \star \delta^{13}C_f) + (C_p \star \delta^{13}C_p) \qquad (3)$$

where C_S is the total C content of the soil layer, C_f and C_p are the relative proportions of forest and pasture carbon, and $\delta^{13}C_s$, $\delta^{13}C_f$ and $\delta^{13}C_p$ are the respective $\delta^{13}C$ values of the total soil layer, forest-derived C and pasture-derived C (Balesdent *et al.*, 1987; Choné *et al.*, 1991). The measured value of $\delta^{13}C_f$ in the forest of each chronosequence was used as the estimate of $\delta^{13}C_f$ for the pastures in that chronosequence. A value of -13 $\permil$, typical of the $\delta^{13}C$ of C_4 pasture grasses, was used as the estimate of $\delta^{13}C_p$ (Cerri *et al.*, 1991; Bonde *et al.*, 1992b).

Results

We measured relatively small changes to a variety of soil characteristics as a result of pasture establishment along the two chronosequences. Soil pH showed a similar pattern of lowest values in the forests, highest values in the 8-year-old pastures and lower but still elevated values in the 20-year-old pastures (Table 1). Bulk density did not change along chronosequence I and the only statistically significant differences in soil densities in chronosequence II were lower densities in the pastures at 10 to 20 and 20 to 30 cm depths (Table 1). Soil texture differed along the chronosequences but differences did not clearly relate to pasture age (Table 1).

Percent soil C in chronosequence I was higher in pastures compared with the forest but values at each depth were not statistically different between land uses in either chronosequence (Table 2). Both chronosequences showed trends of greater percent soil N in pastures compared with the original forest, but relatively low soil percent nitrogen and high variability resulted in nonsignificant differences between land uses (Table 2). Soil percent C and N were approximately 2 to 4 times greater at 0 to 10 cm depth than at 20 to 30 cm. Changes in soil percent C and N were also greater at the shallower depth.

Total soil C stocks to 30 cm depth were higher in pastures than in the original forest in chronosequence I and significantly higher than the forest in the 20-year-old pasture (Table 2). Soil C stocks in chronosequence II did not show a significant change with change in land use. Soil N stocks to 30 cm showed the same pattern as C stocks and were significantly greater in the 20-year-old pasture of chronosequence I compared with the original forest but not different between land uses in chronosequence II (Table 2).

The $\delta^{13}C$ value of bulk soil at 0 to 10 cm depth increased with pasture age from approximately -27$\permil$ to -28$\permil$ in the forests to approximately -20 $\permil$ in the 20-year-old pastures of both chronosequences (Figure 1). Differences of $\delta^{13}C$ between forest and 20-year-old pastures at 10 to 20 cm depth were smaller, (4.1 to 4.6 $\permil$), and those at the 20 to 30 cm smaller yet (2.3 to 2.4 $\permil$), reflecting greater inputs of pasture-derived C at shallower depths.

The total soil C stock derived from C_4 pasture grasses increased with pasture age, but a large portion of the soil C stock in both chronosequences consisted of residual forest C (Figure 2). Carbon derived from the original forest comprised 64% to 83% of total soil C at the 0 to 10 cm depth in 8-year-old pastures and 48% to 50% in 20-year-old pastures (Table 2). Carbon turnover was slower at greater soil depths. Carbon derived from pasture grasses made up 50% to 52% of total soil C in 20-year-old pastures at the 0 to 10 cm depth but only 18 to 19% of soil total C in the same pastures at 20 to 30 cm depth (Table 2).

Table 1. Vegetation and soil physical properties along two forest-to-pasture chronosequences on na Ultison and Alfisol near Ouro Preto, state of Rondonia

Chronosequence	Location	Land Use	Vegetation	Depth cm	pH H_2O	Bulk Density g.cm⁻³	Clay %	Silt %	Sand %
I	Fazenda Benjamin	Forest	Open tropical moist forest	0-10	4.8	1.37	12	3	85
				10-20	4.1	1.66	18	3	79
				20-30	4.2	1.60	20	5	75
		8 yr Pasture	Panicum Maximum	0-10	5.9	1.53	16	13	71
				10-20	6.0	1.65	22	7	71
				20-30	6.1	1.56	24	6	70
		20 yr Pasture	B. brizantha & B. decumbens	0-10	5.4	1.46	16	4	80
				10-20	5.5	1.60	18	5	77
				20-30	5.5	1.54	20	5	75
II	Fazenda Lenk	Forest	Open tropical moist forest	0-10	5.3	1.24	23	16	62
				10-20	4.8	1.46	26	13	61
				20-30	5.2	1.47	26	12	62
		8 yr Pasture	Panicum maximum	0-10	5.8	1.25	30	10	60
				10-20	6.0	1.32	34	10	56
				20-30	5.7	1.28	34	12	54
		20 yr Pasture	B. brizantha	0-10	5.7	1.19	34	10	56
				10-20	5.9	1.29	36	11	53
				20-30	5.9	1.24	38	10	52

Table 2. Percent carbon and nitrogen, carbon and nitrogen stocks, percent of total carbon derived from the original forest, lignocellulose index and C:N ratio along two forest-to-pasture chronosequences near Ouro Preto, state of Rondônia. Error bars are ± 1 standard deviation

Chrono-sequence	Land Use	Depth cm	C %	Total C kg/m²	N %	Total N kg/m²	Forest-derived C %	Forest-derived C kg/m²	LCI	Mass C:N
I	Forest	0-10	1.05±0.47	1.44±0.66	0.06±0.07	0.09±0.08	100	1.44±0.66	0.81	15.8
		10-20	0.50±0.05	0.83±0.08	0.04±0.01	0.07±0.02	100	0.83±0.08	0.86	12.3
		20-30	0.44±0.08	0.70±0.13	0.02±0.03	0.04±0.04	100	0.70±0.13	0.87	20.0
		0-30		2.98±0.68		0.19±0.11	100	2.98±0.68		15.4
	Pasture 8 yrs	0-10	1.55±0.41	2.37±0.65	0.12±0.02	0.18±0.03	64	1.52±0.41	0.85	12.9
		10-20	0.51±0.10	0.83±0.17	0.03±0.04	0.06±0.05	80	0.67±0.14	0.87	14.4
		20-30	0.44±0.09	0.65±0.14	0.03±0.01	0.06±0.01	91	0.59±0.12	0.88	11.6
		0-30		3.85±0.68		0.30±0.06	72	2.77±0.45		13.0
	Pasture 20 yrs	0-10	1.53±0.36	2.23±0.55	0.13±0.03	0.19±0.05	50	1.11±0.27	0.79	11.9
		10-20	0.80±0.17	1.28±0.27	0.08±0.02	0.13±0.03	66	0.84±0.18	0.85	10.2
		20-30	0.61±0.14	0.96±0.22	0.07±0.02	0.40±0.03	81	0.77±0.18	0.90	8.7
		0-30		4.47±0.65		0.42±0.06	61	2.72±0.37		10.6
II	Forest	0-10	2.19±1.07	2.71±1.34	0.12±0.04	0.15±0.05	100	2.72±1.34	0.86	18.2
		10-20	0.82±0.26	1.20±0.38	0.07±0.01	0.11±0.01	100	1.20±0.33	0.89	11.1
		20-30	0.61±0.15	0.90±0.23	0.04±0.02	0.06±0.03	100	0.90±0.23	0.92	16.4
		0-30		4.81±1.41		0.31±0.06	100	4.81±1.41		15.4
	Pasture 8 yrs	0-10	1.64±0.29	2.04±0.38	0.15±0.05	0.19±0.07	83	1.69±0.31	0.82	11.0
		10-20	0.98±0.09	1.29±0.46	0.13±0.04	0.175±0.06	92	1.18±0.11	0.84	7.8
		20-30	0.77±0.08	1.23±0.12	0.08±0.01	0.12±0.02	94	1.15±0.11	0.85	10.2
		0-30		4.56±0.41		0.47±0.09	88	4.03±0.35		9.7
	Pasture 20 yrs	0-10	2.33±0.38	2.77±0.46	0.22±0.01	0.26±0.02	48	1.34±0.22	0.81	10.7
		10-20	0.98±0.16	1.26±0.21	0.10±0.01	0.14±0.01	68	0.87±0.15	0.83	9.3
		20-30	0.66±0.04	1.12±0.06	0.04±0.04	0.07±0.05	82	0.92±0.05	0.89	15.8
		0-30		5.15±0.51		0.47±0.06	61	3.12±0.27		11.1

Mass C:N ratios were lower in the surface soils of all the pastures compared with the original forest (Table 2). C:N ratios were generally in the range of 8 to 20, but generally lower C:N ratios in the pastures is consistent with relatively greater accumulation of N relative to C in the older pastures. Lignocellulose index (LCI) values for bulk soils at all sites along the chronosequences were approximately 0.8 or greater (Table 2). LCIs increased with soil depth but showed no clear pattern between forests and pastures and with increasing pasture age.

Discussion

Soil properties, carbon and nitrogen stocks

Rapid land colonization and high turnover of land tenure in Rondônia make long-term chronological studies of soil properties following deforestation extraordinarily difficult. Chronosequence studies using information derived from local land managers and confirmed by remotely sensed images represent a sensible alternative approach, although potential problems of preexisting differences in soil characteristics are associated with any chronosequence study. The

chronosequences reported here represent the best present regional information on long-term soil changes, despite differences in soil classification, clay content and vegetation history all varied to some degree. In our judgment, the soils across each chronosequence shared similar pedogenic histories and the different soil classifications into which they fall were more of an artifact of the classification systems than genetic differences of ecological significance. Given the relatively high spatial variability of soils in Rondonia, our experience is that clay content variation in the range of about 10-12 % will be present even in directly adjacent sites, especially given the relatively severe constraint of detailed knowledge of land use history. Differences in vegetation are unavoidable because planting P. maximum pastures was the regional practice in the 1970s, but species of Brachiaria gained favor during the 1980s.
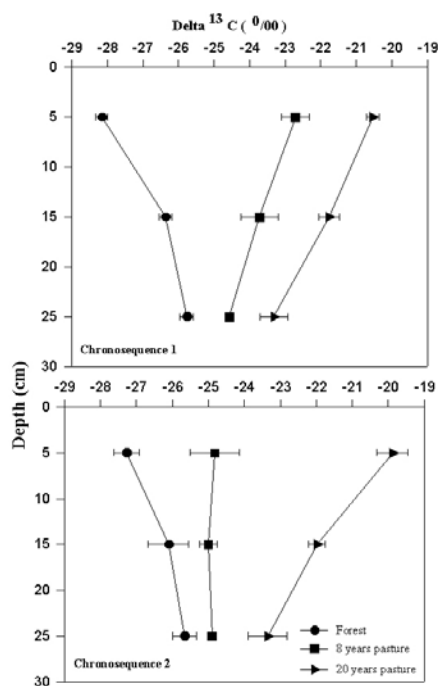

Figure 1. δ^{13}C distribution in soils profiles from forest and pasture sites in chronosequence 1 and chronosequence 2 with the respective standard deviations

The two chronosequences at Ouro Preto represent important Amazon Basin soil types. Red-yellow podzolic soils (Argissolo) cover approximately 30% of the Basin and latosols cover an additional 42% of the Basin, with red-yellow latosols making up the largest single class, at 20% (Moraes at al., 1995). Red latosols cover a smaller area of only approximately 2%, of the total Basin

area, but their low acidity and high base saturation, make them important agricultural soils (Richter and Babbar, 1991).
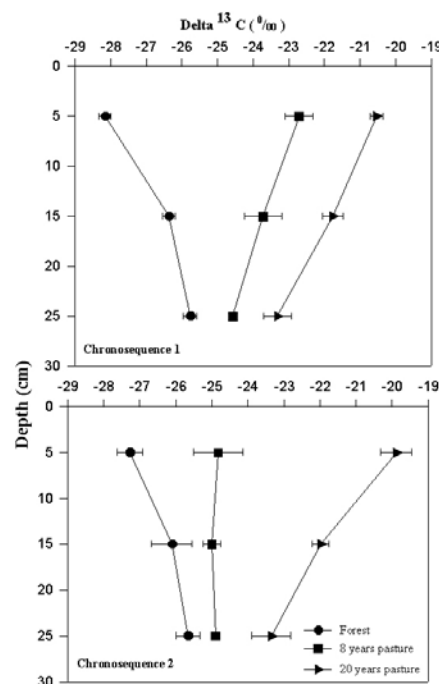

Figure 2. The dynamics of total soil carbon, carbon derived from forest and carbon derived from pasture vegetation in the top 0-30cm soil layer in chronosequences 1 and 2

Our results of no change in soil bulk density in 8- and 20-year-old pastures differ from the small number of studies that have examined soil bulk density in pastures created on converted tropical forest soils, which indicate some compaction of the surface soil takes place and that bulk density increases slightly compared with the original forest (Hect, 1982; Buschbacher *et al.*, 1988; Veldkamp, 1993). We suspect that regional differences in soil type and management practices can lead to differing degrees of soil compaction following deforestation. The direct conversion of forest to pasture and absence of mechanization in the chronosequences we examined may reduce compaction. Some studies on Amazon Basin oxisols indicate that the method of land clearing is an important determinant of the degree of soil compaction, with mechanized clearing leading to greater increases in soil bulk density (Buschbacher *et al.*, 1988). Development of an understanding about the role of soil type and management practices on soil compaction and related effects on soil structure and water dynamics will likely be important for devising management practices to sustain pasture productivity.

Soil pH remained elevated in pastures through 20 years following forest conversion. Although collection of soil for pH from only one pit at each site prevented tests for pH differences between land uses, the similar patterns observed in both chronosequences are consistent with the increases in pH near the soil surface commonly observed following the burning that accompanies forest conversion (Sánchez *et al.*, 1983; Luizão *et al.*, 1992; Bonde *et al.*, 1992a). The common practice in the Ouro Preto region of reburning pastures every 3 to 7 years to control weeds may play a role in maintaining elevated soil pH in older pastures.

Our findings of an increase or no change in surface soil C stocks following forest clearing and pasture establishment differ from the widely held assumption that agricultural use of converted tropical moist forest lowers soil C storage (Detwiler, 1986; Houghton *et al.*, 1991). There are few similar studies of soil C stocks in tropical forests and pastures for comparison with our findings, but there are some indications that either an increase or no net long-term changes in soil C stocks follows pasture creation in other parts of the Amazon Basin. Near Manaus, C stocks at the same depth of 0 to 30 cm showed a similar pattern to that we observed in Chronosequence II, with a 7% decreased of C stock in 2-year-old pasture but an increase of 9% in 8-year-old pasture compared with original forest (Bonde *et al.,* 1992a). Also near Manaus, Choné *et al.* (1991) reported a 24% decrease in C stocks to 20 cm depth in two-year-old pasture and an increase of 7% in 8-year-old pasture. Because these studies do not directly report bulk density, they cannot be corrected to account for the sampling of unequal soil mass that can occur if bulk density changes in pasture soil. Because changes in bulk density were small, correction for sampling of an equal soil mass resulted in differences of 5% or less between corrected and uncorrected estimates of soil C and N stocks, but these sampling errors can be substantial if changes in bulk density are large (Veldkamp, 1993). When corrected for equal soil mass, Veldkamp (1993) observed 6% and 28% decreases in soil C stocks in two 25-year-old Costa Rican pastures compared with the original forest on volcanic soils.

All of these studies show that the largest changes in soil C stocks following conversion to pasture take place in the top 10 cm, which represents the zone of the most active soil C pool sensitive to change with modifications of land use. Moraes *et al.* (1995) estimated that 45% of total Amazon Basin soil C to a depth of 1 m is contained within the upper 20 cm.

The majority of existing data on changes in soil C stocks following forest clearing is derived from conversion to crop agriculture, where patterns of change in soil C stocks may be very different. Soils of sugarcane fields planted on converted oxisols showed declines in total soil C from 7.2 kg.m^{-2} under original forest vegetation to 4.5 kg.m^{-2} after 12 years and 3.9 kg.m^{-2} after 50 years of cultivation (Cerri and Andreux, 1990). Similar trends following cultivation have been observed in a variety of tropical soils (Krebs, 1975; Seubert *et al.*, 1977; Sánchez *et al.*, 1983).

The significant increase in soil N stock of chronosequence I raises questions about the role of soil C and N interactions in soil C storage. The increase in soil total N stocks in the surface 30 cm of the 20-year-old pasture of chronosequence I amounted to 229 g.m^{-2}, or 11.5 g.m^{-2} yr^{-1}. Low concentrations of NH_4^+-N and NO_3^--N in precipitation in remote areas of the Amazon Basin make it unlikely that precipitation can account for more than 0.2 g N m^{-2} yr^{-1} (Andreae *et al.*, 1990). Inputs from N fixation associated with pasture grasses may be larger and could potentially account for the observed increases in soil N stocks and relatively greater increases in soil N stocks compared with C stocks. Boddey and Victória (1986) found that fixation can account for 30 to 40% of the N requirement for species of Brachiaria. Annual values for N fixation of up to 100 g N m^{-2} yr-1 have been reported in association with the roots of many tropical forage grasses (Ayanaba and Dart, 1977) but remain speculative for the Amazon Basin. Soil management after pasture formation can also be an important control on soil N stocks in other locations in the Brazilian Amazon Basin. In Pará, Buschbacher *et al.*, (1988) found no clear relationship between soil N stocks and pasture age, but soil N stocks were lower in intensively used 8-year-old pastures compared with more lightly used pastures with substantial N reserves in slash.

Soil organic matter dynamics

The calculation of the contribution of forest- and pasture-derived C to the total soil C pools based on the $\delta^{13}C$ data showed a general pattern of pasture C augmenting a very slowly declining pool of existing forest-derived C (Figure. 1). Our $\delta^{13}C$ data showed that 60% or more of the original forest soil C remained in pasture soils after 20 years (Figure 1). These findings are similar to those from forest-to-pasture chronosequences on oxisols near Manaus, where C derived from the original forest made up 83% of total surface soil C in 3-year-old pasture and

80% of total soil C in 8-year-old pasture (Bonde *et al.*, 1992a).

The large amount of forest C remaining in the soil of old pastures indicates that these pasture soils have a large, stable, refractory C pool derived from the previous forest vegetation. There is evidence that this pool of refractory forest C is associated with the soil clay fraction. Bonde *et al.* (1992b) found that in an actively cultivated sugarcane field on an oxisol, forest C made up 62% of the C associated with the clay (<2 μm) soil fraction after 12 years and 51% after 50 years. In contrast, 83 and 93% of the original forest-derived C associated with the coarse and fine sand fractions decomposed after 12 and 50 years (Bonde *et al.*, 1992b). Similar slow turnover of clay-associated organic matter has been demonstrated for tropical savanna soils (Martin *et al.*, 1990). The C that is actively cycling in soils of pasture created from converted forest may be a relatively small fraction of total soil C that is derived from pasture vegetation. The age of pasture at which pasture-derived C replaces forest-derived C as the most important substrate for soil microbiota is not known.

Lower C:N ratios suggested a gradual increase of soil organic matter quality with conversion to pasture. Values for LCI for both forest and pasture soils were similar and high relative to other reported values for soils (Melillo *et al.*, 1989). High amounts of lignin relative to more labile carbohydrates in soil organic matter and small differences between forest and pasture soils further support the conclusion that there is in pasture soils a large refractory forest-derived C pool. The LCI of this large pool probably masks any changes in quality of the labile organic matter that occur along the chronosequence.

Implication for regional carbon and nitrogen cycles

The patterns of change in soil C stocks that we found could have important implications for calculations of total C fluxes resulting from land use change in the Amazon Basin. Most soil C models (Detwiler and Hall, 1988; Houghton *et al.*, 1991) have assumed declines in soil C content following forest conversion for both pasture and crop agriculture. Our results that show little change or an increase of pasture soil C stocks with time emphasize the importance of separating categories of agricultural land use in future models of the effects of land use change on C stocks of tropical soils. Direct conversion to pasture is only one of a number of land use pathways now occurring in the Amazon Basin. We currently do not have the data to extrapolate to other soil types and land use histories where soil responses to deforestation and pasture productivity may be different. Millions of hectares of the tropics are now covered by pastures and pasture area will continue to increase given present rates of land use conversion. A better understanding of the processes controlling soil C and N stocks and dynamics in pastures and how they compare with the original forest vegetation will allow more precise estimation of the effects of land use change at larger scales.

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