

SOIL CARBON AND NITROGEN STOCKS FOLLOWING FOREST CLEARING FOR PASTURE IN THE SOUTHWESTERN BRAZILIAN AMAZON

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Abstract. Tropical soils contain large stocks of carbon and nitrogen that can be altered by clearing for agriculture. In the Brazilian Amazon, cattle pasture is the predominant use for cleared forest lands. We examined changes to soil bulk density and C and N stocks in seven chronosequences, each consisting of an intact forest and pastures of different ages created directly from cleared forest (7 forests, 18 pastures), along a 700-km transect in Rondônia in the southwestern Amazon Basin. The transect included sites with a similar climate but a range of soil types. We used soil $\delta^{13}\text{C}$ distributions to determine the origin of soil C and to infer changes to soil C cycling patterns after forest clearing. Soil bulk density increased under pasture; these increases were significant in 6 of 18 pastures examined. Changes in C stocks to a depth of 30 cm under pasture ranged from a loss of 0.72 kg/m² to an increase of 1.77 kg/m². Soil C stocks increased in 14 of 18 pastures, but these increases were significant in only 4 pastures. Changes in soil N stocks to a depth of 30 cm ranged from a loss of 0.25 kg/m² to a gain of 0.23 kg/m² and showed a similar pattern to C, except in one site where we measured significant N loss. Five of 18 pastures accumulated significant amounts of N, and one pasture lost a significant amount of N. Soil $\delta^{13}\text{C}$ values were greater in pastures than in the original forests, and $\delta^{13}\text{C}$ values increased with a longer time under C₄ pasture vegetation. Bulk density increases were greater on soils with higher clay contents. Carbon accumulation increased with pasture age but was independent of soil texture. Soil C increases to a depth of 30 cm of up to 1.77 kg/m² amounted to an increase of >50% of the original soil C stock and represented up to 12% of the C in the biomass of forest vegetation. In contrast, changes to soil N stocks in the range of 0.25 kg/m² approximately equaled the N stock in the original forest vegetation. Our results indicated that when site history was controlled by considering only pastures formed directly from cleared forest, C and N accumulation was the dominant trend in pasture soils. Absence of a correlation between C and N accumulation and soil texture suggested that site history and management may be more important than soil type as determinants of the direction and magnitude of changes in soil C and N stocks.

Key words: Amazon; Brazil; land-use change; organic matter; pasture; Rondônia; soil; tropical forests.

INTRODUCTION

Soils play an important role in the C and N cycles of the earth. At the global scale, they contain ~75% of the C and >90% of the N in the terrestrial biosphere (Schlesinger 1986). Human alteration of natural ecosystems for agriculture is an important component of global environmental change, and has the potential to alter soil C and N storage. These changes may allow soils to become significant sources of C to the atmosphere (Houghton et al. 1983, Detwiler and Hall 1988). Changes to surface soil organic C and N stocks and cycling patterns are also important indicators of soil fertility and agricultural potential (Tiessen et al. 1994).

In recent decades, tropical forests have replaced temperate forests and grasslands as the region of most rapid land cover conversion (Turner et al. 1990, Ojima et al. 1994). The Brazilian Amazon Basin is the world's largest region of intact tropical forest, and is being deforested at the rate of ~15 000 km²/yr (INPE 1992, Skole and Tucker 1993). Pastures represent the largest use of converted forest lands (Fearnside 1987, Serrão 1992). Despite rapid rates of conversion to pasture, there is currently little information on changes in pasture soil C or N stocks and cycling patterns. In some locations in the Amazon, the productivity of pasture grasses declines over time pastures, but soil C concentrations show no clear trends (Falesi 1976, Serrão et al. 1979, Hecht 1982). In other locations, C inputs from roots of pasture grasses cause increased pasture soil C stocks (Choné et al. 1991). Trumbore et al. (1995) report both

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increases and decreases, depending on pasture management. A better understanding of the direction and magnitude of these changes is important for predicting the effects of land-use change on soil fertility and its consequences for the global C cycle. In particular, we need to understand the role played by factors such as time since land cover conversion and soil mineralogy in soil organic matter loss or accumulation.

The maintenance of soil C in pasture soils depends on both the stability of organic matter derived from the former forest vegetation and rates of organic matter input from planted pasture grasses. Stable C isotopes provide insight into the relative contributions of forest-derived and pasture-derived C in agricultural soils (Cerri et al. 1985, Balesdent et al. 1987, Vitorello et al. 1989). Organic matter formed from forest and pasture vegetation is naturally labeled with a different C isotopic $^{13}\text{C}/^{12}\text{C}$ signal because forest plants use a C_3 photosynthetic pathway, while planted tropical forage grasses use a C_4 pathway. The difference between forest vegetation $\delta^{13}\text{C}$ values ($\sim -28\text{‰}$) and pasture vegetation $\delta^{13}\text{C}$ values ($\sim -13\text{‰}$) allows determination of the relative contributions of forest- and pasture-derived C to the total soil C pool by using simple mixed models (Cerri et al. 1985).

In this paper, we examine changes in soil C and N stocks and the origins of soil C following forest clearing and direct planting to pasture at sites distributed across the state of Rondônia in the southwestern Brazilian Amazon Basin. Rondônia has experienced high deforestation rates since the early 1980s. We asked the following questions: (1) Do soil C and N stocks increase or decrease after forest conversion to pasture? (2) What is the relative importance of residual forest-derived C and new pasture-derived C inputs to total soil C stocks? (3) What soil characteristics influence the changes to soil C and N stocks? We measured C and N stocks in chronosequences that consisted of forest and pastures of different ages.

METHODS

Study areas

We examined seven chronosequences of forest and pastures of different ages on cattle ranches along a 700-km transect along the Cuiabá-Porto Velho highway (BR-364) that runs from Porto Velho to Vilhena (Fig. 1). The transect incorporated only small climatic variation but a large variation in soil type. Precipitation ranged from 2.27 m/yr in Porto Velho to 2.09 m/yr in Vilhena (SUDAM 1984). Mean annual temperature was $24.4^{\circ}\text{--}25.6^{\circ}\text{C}$ in Porto Velho and $18.8^{\circ}\text{--}20.3^{\circ}\text{C}$ in Vilhena (Bastos and Diniz 1982). Mean monthly temperature varied by $<4^{\circ}\text{C}$ at all sites.

Natural vegetation over most of Rondônia is moist, open tropical forest with high numbers of palms. The end of the transect at Vilhena represented the transition between closed forest and campo cerrado vegetation.

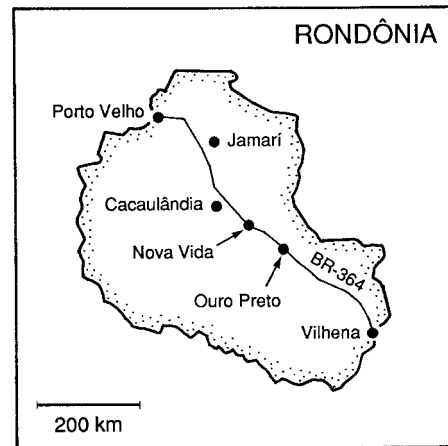


FIG. 1. The Brazilian Amazon Basin state of Rondônia and the location of the chronosequences.

All other forests were of larger stature and typical of most remaining terra firme forest in Rondônia. Our observations and information provided by fazenda (ranch) owners showed that 1–3 trees/ha were removed from all of the forests by selective logging during the 10 years prior to our sampling. This level of disturbance is typical of accessible forest in the region. We selected sites only in areas of flat or gently rolling topography. One ranch, Nova Vida, was the site of previous investigations of soil C and N dynamics (Neill et al. 1995, Moraes et al. 1996).

Each sequence consisted of a reference forest and pastures of different ages. We restricted pastures to sites that were converted directly to pasture by cutting, burning, and planting pasture grasses in the same year. Clearing involved cutting brush in March, cutting large trees in June or July, burning the slash in late August or September, and seeding pasture grasses in December or January. A second burn to kill tree stump regrowth and to reduce the volume of downed wood typically occurred 2–3 yr after the initial clearing. All pastures were managed by periodic burning approximately every 4–7 yr to control woody plants. Pastures were never mechanized, nor were they ever amended with fertilizer or lime. This was typical of the management of pastures in the region. Vegetation consisted of the pasture grasses most commonly planted in Rondônia, which are *Panicum maximum* and three species of the genus *Brachiaria*, *B. humidicola*, *B. decumbens*, and *B. brizantha* (Table 1). *B. brizantha* replaced other grasses as the species of choice among ranchers during the late 1980s. The older pastures were burned and replanted with this species.

Soil types found along the transect included the dominant soils that occur in Rondônia and in the Brazilian Amazon Basin. These included dystrophic red-yellow podzolics (Udults), which cover $\sim 22\%$ of the Brazilian Amazon; red-yellow latosols (Udults, Udoxes), which cover 20%; yellow latosols (Udoxes), which cover 18%; and eutrophic red and red-yellow podzolics

TABLE 1. Land use, pasture age, vegetation, and soil chemical characteristics at 0–10 cm sample depths in seven chronosequences in Rondônia.

Location	Land use	Vegetation	Soil type	Clay (%)	Soil texture class	pH of H ₂ O	ECEC† (cmol _c /kg)	Base saturation (%)	Acid-extractable P (mg/kg)
Porto Velho	forest		red-yellow latosol (Hapludox)	58	clay	3.90	3.55	8	2.0
Cacaulândia	7-yr-old pasture	<i>Brachiaria brizantha</i>	red-yellow latosol (Hapludox)	55	clay	5.21	5.07	25	2.2
	forest		red-yellow podzolic (Paleudult)	16	sandy loam	5.38	5.84	73	3.6
Nova Vida—Chronosequence 1	8-yr-old pasture	<i>B. humidicola</i>	red-yellow podzolic (Paleudult)	13	loamy sand	6.17	3.84	68	4.5
	forest		red-yellow podzolic latosol (Kandiudult)	22	sandy loam	4.78	6.09	45	2.8
	3-yr-old pasture	<i>B. brizantha</i>	red-yellow podzolic latosol (Kandiudult)	24	sandy loam	6.60	6.90	93	4.0
	5-yr-old pasture	<i>B. brizantha</i>	red-yellow podzolic latosol (Kandiudult)	18	sandy clay loam	7.18	8.41	96	2.5
	9-yr-old pasture	<i>Panicum maximum</i> , <i>B. humidicola</i>	red-yellow podzolic latosol (Kandiudult)	25	sandy loam	6.05	5.32	91	2.5
	13-yr-old pasture	<i>P. maximum</i>	red-yellow podzolic latosol (Kandiudult)	22	sandy loam	6.06	3.79	86	2.3
	20-yr-old pasture	<i>B. brizantha</i>	red-yellow podzolic latosol (Kandiudult)	23	sandy clay loam	5.67	4.57	58	2.5
	41-yr-old pasture	<i>P. maximum</i>	red-yellow podzolic latosol (Kandiudult)	25	sandy clay loam	5.74	4.75	73	2.7
	81-yr-old pasture	<i>B. brizantha</i>	red-yellow podzolic (Paleudult)	15	loamy sand	5.86	4.74	82	9.5
	forest		red-yellow podzolic (Paleudult)	11	loamy sand	4.92	4.59	72	4.0
Nova Vida—Chronosequence 2	3-yr-old pasture	<i>B. brizantha</i>	red-yellow podzolic (Paleudult)	23	sandy loam	5.12	6.26	73	10.4
	5-yr-old pasture	<i>B. brizantha</i>	red-yellow podzolic (Paleudult)	13	loamy sand	6.51	7.06	96	3.4
	20-yr-old pasture	<i>P. maximum</i>	red-yellow podzolic (Paleudult)	19	loamy sand	6.10	3.28	87	3.4
	forest		red-yellow podzolic (Paleudult)	12	loamy sand	4.80	5.12	40	1.8
Ouro Preto—Benjamin	8-yr-old pasture	<i>P. maximum</i>	red-yellow podzolic (Paleudult)	16	loamy sand	5.90	12.11	73	19.5
	20-yr-old pasture	<i>B. brizantha</i> , <i>B. decumbens</i>	red-yellow podzolic (Paleudult)	16	sandy clay loam	5.40	6.42	54	2.5
Ouro Preto—Lenk	forest		red-yellow podzolic (Paleudalf)	23	sandy clay loam	5.30	8.06	54	2.5
	8-yr-old pasture	<i>P. maximum</i>	red-yellow podzolic (Paleudalf)	30	sandy clay loam	5.80	9.32	76	5.0
	20-yr-old pasture	<i>B. brizantha</i>	red-yellow podzolic (Paleudalf)	34	sandy clay loam	5.70	10.29	68	3.0
Vilhena	forest		yellow latosol (Hapludox)	75	clay	3.70	4.46	7	2.5
	7-yr-old pasture	<i>B. brizantha</i>	yellow latosol (Hapludox)	76	clay	4.68	4.76	25	2.2
	12-yr-old pasture	<i>B. brizantha</i>	yellow latosol (Hapludox)	67	clay	4.52	4.26	15	2.5

† ECEC = effective cation exchange capacity.

(Udalfs), which cover 4% (Moreas et al. 1995). Soil texture classes along the transect ranged from very clayey yellow latosols (Hapludoxes) with clay contents of 67–75% to sandy red-yellow podzolics (Paleudults) with clay contents as low as 11% (Table 1).

Sample collection and analysis

Soil was collected from pits at each site arranged either in a straight line 50 m apart (Ouro Preto), in a

straight line 25 m apart (Porto Velho, Cacaulândia, Vilhena), or in a cross with points 25 m apart (Nova Vida). Five pits were dug, except at Ouro Preto—Fazenda Benjamin, where sampling was from four pits. Samples for bulk density, C and N concentrations, and $\delta^{13}\text{C}$ were collected with volumetric rings from 0–5, 5–10, 10–20, and 20–30 cm depths in each pit. The exception was at Ouro Preto, where density was determined from volumetric cylinders taken from the four walls of a

larger middle pit. At all locations, soil from each depth for soil characterization (texture, pH, cations and effective cation exchange capacity, and acid-extractable P) was collected either from the volumetric rings or from pit faces. Sampling at Ouro Preto was conducted during September–October 1990. The two sequences at Nova Vida were sampled in July 1992. Sites at Porto Velho, Cacaúlândia, and Vilhena were sampled during October–November 1993.

All samples for density determination were weighed wet and a subsample was dried at 105°C for wet to dry mass conversion. Samples were further prepared by air drying and sieving through 2-mm mesh to remove stones and root fragments. Exchangeable cations at each site were characterized by analyzing one sample made up of equal portions of soil from each pit at each depth. Potassium, calcium, and magnesium were extracted with ammonium acetate at pH 7 and analyzed by emission spectrophotometry. Aluminum was extracted with unbuffered KCl and analyzed by emission spectrophotometry. Phosphorus was measured by extraction with 0.05 mol/L HCl and 0.0125 mol/L H₂SO₄ and measured by ICP spectrometry. Five samples at each depth at each site were analyzed for pH, total C, and total N. Soil pH was measured in water (2.5:1) on air-dried soil. A subsample of air-dried soil was ground to a fine powder in a mortar and pestle and oven-dried to 60°C for analysis of total C, total N, and $\delta^{13}\text{C}$. Total C and N were analyzed by combustion on a Perkin-Elmer 2400 Elemental Analyzer (Norwalk, Connecticut).

Three samples from 0–5, 5–10, 10–20, and 20–30 cm depths (Nova Vida and Ouro Preto) or two samples from 0–5 and 5–10 cm and one sample from 10–20 cm and 20–30 cm depths (Porto Velho, Cacaúlândia, and Vilhena) were analyzed for $\delta^{13}\text{C}$ on a Micromass 602 E mass spectrometer (Beverly, Massachusetts) or on a Finnigan Δ -S mass spectrometer (San Jose, California). The ratio of $^{13}\text{C}/^{12}\text{C}$ of the sample was expressed in δ values in parts per thousand relative to the PDB standard, according to the formula:

$$\delta^{13}\text{C} = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 10^3$$

where $R = ^{13}\text{C}/^{12}\text{C}$.

Soil C and N stocks were calculated from soil C and N concentrations and dry bulk density. Because bulk density may change after conversion to pasture, errors in estimated C and N stocks may occur when sampling is based on a fixed depth (Davidson and Ackerman 1993, Veldkamp 1994). Therefore, 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 pasture C stocks based on a depth of slightly less than 30 cm when bulk density was greater in pasture and a depth slightly greater than 30 cm when bulk density was less in pasture. We assumed that the C and N content of soil in the 20–30 $\pm a$ cm soil layer used

to calculate stocks was equal to that in the sampled 20–30 cm layer. Errors associated with C stocks were determined from the variances associated with bulk density and percentage C at each depth as follows:

$$s^2_{\text{CD}} = (s^2_{\text{C}} \times s^2_{\text{D}}) + (x^2_{\text{C}} \times s^2_{\text{D}}) + (x^2_{\text{D}} \times s^2_{\text{C}})$$

where s^2_{C} and s^2_{D} are the variances of percentage of C and density; and x_{C} and x_{D} are the mean percentage of C and density. Errors associated with N stocks were calculated the same way. Differences in bulk density, pH, and C and N stocks between pastures and the original forest were determined using *t* tests. Relationships among changes in density, C and N stocks, soil clay content, and pasture age were determined with multiple regression using the REG procedure of SAS (SAS Institute 1987).

Relative contributions of forest- and pasture-derived soil C were calculated for each soil layer as a simple linear mixture of forest (C₃) carbon and pasture (C₄) carbon, according to the equation:

$$C_{\text{t}} \times \delta^{13}\text{C}_{\text{t}} = (C_{\text{f}} \times \delta^{13}\text{C}_{\text{f}}) + (C_{\text{p}} \times \delta^{13}\text{C}_{\text{p}})$$

where C_{t} is the total C content of the soil layer, C_{f} and C_{p} are the relative proportions of forest- and pasture-derived C, and $\delta^{13}\text{C}_{\text{t}}$, $\delta^{13}\text{C}_{\text{f}}$, and $\delta^{13}\text{C}_{\text{p}}$ are the respective $\delta^{13}\text{C}$ values of the total soil C, forest-derived C, and pasture-derived C (Balesdent et al. 1987, Choné et al. 1991). The measured value of $\delta^{13}\text{C}_{\text{f}}$ at each depth in the forest of each chronosequence was used as the estimate of the original $\delta^{13}\text{C}_{\text{f}}$ for that chronosequence. We used the pasture grass value of -13‰ from Nova Vida as the estimate of $\delta^{13}\text{C}_{\text{p}}$.

RESULTS

Soil characteristics

Soil pH at 0–10 cm sample depth in forests ranged from 3.70 to 5.38 (Table 1). Forest soil effective cation exchange capacity (ECEC) ranged from 4.46 cmol_c/kg with a base saturation of 7% in a Hapludox in Vilhena to 8.06 cmol_c/kg with a base saturation of 54% in a Paleudalf at Fazenda Lenk in Ouro Preto (Table 1). Acid-extractable P in forest soils ranged from 1.8 to 4.0 mg/kg (Table 1). The pH of soils of pastures <10 yr old was one unit or more higher than that of the original forest. The pH declined in older pastures but remained elevated compared with that of the forests. Concentrations of ECEC and P in pastures were more variable than pH, but they also tended to be higher in young pastures (Table 1). They typically did not remain elevated in pastures older than 10 yr. In Cacaúlândia and Vilhena, ECEC and P concentrations in pastures changed little compared with the original forest.

Bulk density and carbon and nitrogen concentrations

Bulk density at 0–10 cm in forest soils varied more than two-fold across the transect, from 0.59 to 1.37 g/cm³ (Table 2). Lower densities occurred at the ends of the transect in Porto Velho and Vilhena, where soil

TABLE 2. Changes in soil bulk density, carbon and nitrogen concentrations, and carbon and nitrogen stocks in seven chronosequences in Rondônia (data are presented as means \pm 1 SE).

Location	Land use	Sample depth 0–10 cm			Sample depth 0–30 cm	
		Bulk density (g/cm ³)	C (mg/g)	N (mg/g)	C stock (kg/m ²)	N stock (kg/m ²)
Porto Velho	forest	0.88 \pm 0.02	29.16 \pm 1.16	2.37 \pm 0.10	6.20 \pm 0.23	0.50 \pm 0.02
	7-yr-old pasture	1.12 \pm 0.02**	28.11 \pm 2.60	2.14 \pm 0.17	6.10 \pm 0.64	0.48 \pm 0.04
Cacaulândia	forest	1.07 \pm 0.02	17.14 \pm 1.56	1.86 \pm 0.16	3.93 \pm 0.28	0.45 \pm 0.03
	8-yr-old pasture	1.26 \pm 0.03*	14.30 \pm 2.32	0.90 \pm 0.15**	3.21 \pm 0.43	0.20 \pm 0.03**
Nova Vida–Chronosequence 1	forest	1.28 \pm 0.03	12.18 \pm 1.60	1.09 \pm 0.10	3.23 \pm 0.32	0.27 \pm 0.02
	3-yr-old pasture	1.36 \pm 0.03	12.49 \pm 1.53	0.90 \pm 0.09	3.46 \pm 0.30	0.26 \pm 0.02
	5-yr-old pasture	1.36 \pm 0.02	17.53 \pm 3.79	1.33 \pm 0.27	4.38 \pm 0.94	0.35 \pm 0.08
	9-yr-old pasture	1.50 \pm 0.03*	15.50 \pm 1.79	1.16 \pm 0.12	3.98 \pm 0.38	0.31 \pm 0.03
	13-yr-old pasture	1.38 \pm 0.26	14.95 \pm 2.95	0.97 \pm 0.14	3.55 \pm 0.71	0.24 \pm 0.03
	20-yr-old pasture	1.31 \pm 0.03	16.40 \pm 1.36	1.13 \pm 0.10	3.88 \pm 0.29	0.30 \pm 0.03
	41-yr-old pasture	1.36 \pm 0.03	18.25 \pm 1.16	1.30 \pm 0.08	4.69 \pm 0.33*	0.37 \pm 0.02*
Nova Vida–Chronosequence 2	forest	1.34 \pm 0.03	20.84 \pm 1.94†	1.60 \pm 0.21	5.00 \pm 0.39*	0.38 \pm 0.05
	3-yr-old pasture	1.22 \pm 0.03	11.44 \pm 1.55	0.67 \pm 0.11	2.74 \pm 0.32	0.15 \pm 0.03
	5-yr-old pasture	1.30 \pm 0.04	14.77 \pm 1.96	1.09 \pm 0.12	3.97 \pm 0.36†	0.31 \pm 0.03*
	20-yr-old pasture	1.29 \pm 0.04	17.38 \pm 3.79	1.16 \pm 0.23	3.65 \pm 0.75	0.25 \pm 0.05
Ouro Preto–Benjamin	forest	1.28 \pm 0.03	17.95 \pm 3.65	0.88 \pm 0.12	3.92 \pm 1.06	0.18 \pm 0.03
	8-yr-old pasture	1.37 \pm 0.05	10.53 \pm 2.37	0.66 \pm 0.35	2.97 \pm 0.30	0.19 \pm 0.05
	20-yr-old pasture	1.53 \pm 0.04†	15.47 \pm 2.07	1.20 \pm 0.10	3.85 \pm 0.30	0.30 \pm 0.03
Ouro Preto–Lenk	forest	1.46 \pm 0.04	15.26 \pm 1.81	1.28 \pm 0.16	4.46 \pm 0.29†	0.42 \pm 0.03*
	8-yr-old pasture	1.24 \pm 0.05	21.93 \pm 5.33	1.21 \pm 0.18	4.81 \pm 0.51	0.31 \pm 0.03
	20-yr-old pasture	1.25 \pm 0.03	16.37 \pm 1.47	1.49 \pm 0.26	4.56 \pm 0.18	0.47 \pm 0.04*
Vilhena	forest	1.19 \pm 0.02	23.31 \pm 1.88	2.19 \pm 0.06**	5.15 \pm 0.23	0.47 \pm 0.03*
	7-yr-old pasture	0.59 \pm 0.02	36.97 \pm 3.34	2.63 \pm 0.24	5.04 \pm 0.29	0.34 \pm 0.02
	12-yr-old pasture	0.93 \pm 0.02**	29.14 \pm 1.97	1.90 \pm 0.13	4.76 \pm 0.26	0.30 \pm 0.02
	pasture	0.96 \pm 0.02**	34.21 \pm 3.46	2.23 \pm 0.19	5.43 \pm 0.54	0.35 \pm 0.03

Note: Symbols indicate where pasture values differed from forest values (*t* tests: † $P < 0.10$, * $P < 0.05$, ** $P < 0.01$).

clay contents were higher. Soil C concentrations ranged from 10.53 mg/g in the relatively sandy soil at Ouro Preto–Benjamin to 36.97 mg/g in the forest at Vilhena, where the clay content was 75% (Table 2). Soil N concentrations followed the same pattern and ranged from a low of 0.66 mg/g at Ouro Preto–Benjamin to 2.63 mg/g at Vilhena (Table 2).

Forest conversion to pasture increased soil bulk densities in the top 10 cm in 17 of 18 pastures examined (Table 2). Pasture densities were significantly greater than the forest in six cases (Table 2). The largest changes occurred in soils at Porto Velho, where density increased by 27%, and at Vilhena, where density increased by 58–63%. Soil bulk density increases were greater in pasture soils with higher clay contents ($n = 18$, $F_{1,16} = 22.84$, $P = 0.0002$). There was no rela-

tionship between density increases and pasture age. Carbon concentration at a depth of 0–10 cm in pastures was variable but increased in comparison with forest in 13 of 18 pastures; however, these increases were significant only in the oldest (81-yr-old) pasture at Nova Vida (Table 2). Changes to N concentrations generally were similar, but Cacaulândia had significantly lower N concentrations than the original forest (Table 2).

Forest soil C stocks to 30 cm ranged from 2.74 kg/m in Chronosequence 2 at Nova Vida to 6.20 kg/m² in Porto Velho (Table 2). Forest soil N stocks ranged from 0.15 kg/m² to 0.50 kg/m² in the same locations (Table 2). Changes in C stocks to 30 cm depth under pasture ranged from a loss of 0.72 kg/m² to an increase of 1.77 kg/m². Increases occurred in 14 pastures, and losses

were detected in 4 pastures. Four pastures had C stocks significantly greater than the forest, and pasture C stocks were never significantly less than in the original forest. Changes in soil N stocks to a depth of 30 cm ranged from a loss of 0.25 kg/m² to a gain of 0.23 kg/m², and showed a similar pattern to C except for Cacaúlândia, where we measured significant N loss. Five of 18 pastures had significantly more N than the forest (Table 2). Changes to soil C stocks were related to pasture age ($n = 18$, $F_{1,16} = 6.16$, $P = 0.0112$), but were independent of soil clay content. Neither pasture age nor clay content were related to changes in soil N stocks.

Soil $\delta^{13}\text{C}$ in the forests fell in a narrow range of -27.0 to -28.5‰ (Fig. 2), reflecting values typical for C_3 plants. The $\delta^{13}\text{C}$ values in all sites showed a regular increase of 1.1 – 2.6‰ between 0 – 5 cm and 20 – 30 cm depths. All pasture soils had higher $\delta^{13}\text{C}$ values than their paired original forest soils (Fig. 2). Pasture soil $\delta^{13}\text{C}$ values typically increased with pasture age, and increases were greatest near the soil surface (Fig. 2), consistent with greater time under C_4 pasture vegetation and with higher rates of organic matter turnover at shallower depths. Only in the Vilhena sequence, where the 7- and 12-yr-old pastures had similar $\delta^{13}\text{C}$ values, did $\delta^{13}\text{C}$ not show a steady increase with pasture age (Fig. 2).

Rates of decay of forest-derived C varied among sites from a loss of 60% of the original forest C in the 8-yr-old pasture at Cacaúlândia to a loss of only 8% at Ouro Preto–Benjamin (Fig. 3). Gains in soil C derived from pasture approximately equaled losses of C derived from forest (Fig. 3). Pasture-derived C comprised 39–45% of total soil C in 20-yr-old pastures and 63% of total soil C in the 81-yr-old pasture at Nova Vida.

DISCUSSION

Chemical characteristics and bulk density

The changes to pH, ECEC, and P that we observed after forest clearing were consistent with patterns reported at a wide variety of tropical sites that were cut and burned either for shifting cultivation or for cattle pasture (Ewel et al. 1981, Hecht 1982, Sanchez et al. 1983, Bonde et al. 1992). Several studies of tropical pastures report increased soil bulk density relative to the original forest (Hecht 1982, Veldkamp 1994, Reiners et al. 1994). Higher soil bulk densities after clearing of tropical forest are associated with changes in pore space distribution and decreased water infiltration and porosity, and reflect the collapse of soil aggregates (Chauvel et al. 1991, Cassell and Lal 1992, Reiners et al. 1994). These previous studies of density examined either volcanic soils or oxisols with relatively high clay contents. Our results suggest that relatively sandy ultisols are less prone to severe compaction. This finding is supported by Desjardins et al. (1994), who reported no increase in density in a 10-yr-old pasture on a Kan-

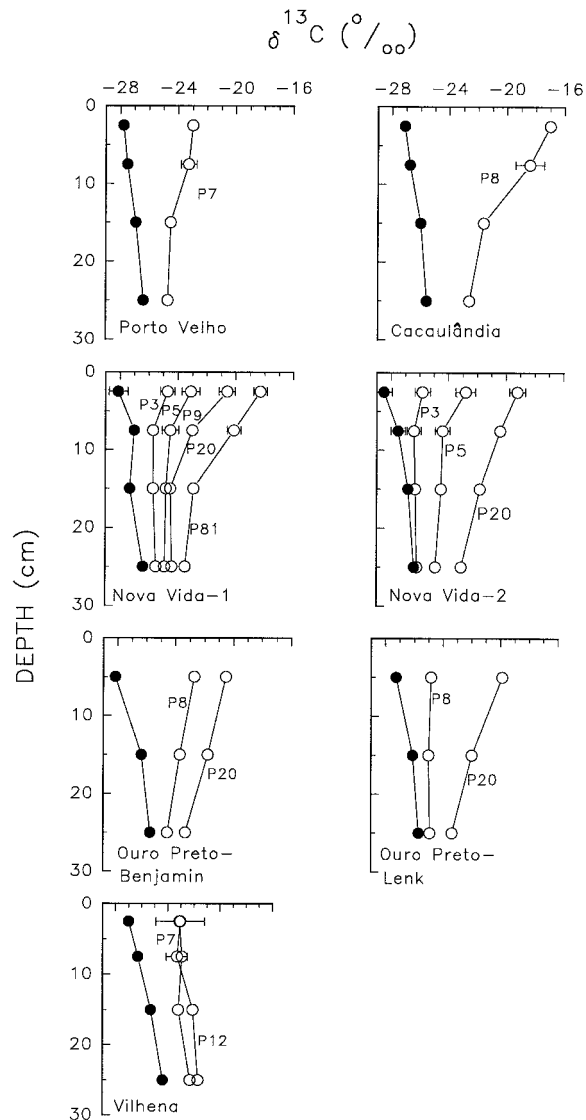


FIG. 2. Soil $\delta^{13}\text{C}$ profiles for seven chronosequences in Rondônia. Solid circles represent forests; open circles depict pastures. Pasture ages are indicated in years. Error bars for 0 – 5 cm and 5 – 10 cm sample depths indicate ± 1 SE and are not shown when they are smaller than the symbol. Values for 10 – 20 cm and 20 – 30 cm sample depths were for single samples.

diudult with 13–20% clay from Capitão Poço in Pará, but Eden et al. (1990) reported modest density increases of 12–26% on ultisols with 22–33% clay in Roraima.

Carbon and nitrogen

Findings from the few studies that have evaluated changes to soil C stocks on the oxisols and ultisols of the Amazon Basin suggest that pasture creation can result in a range of responses, including increases, decreases, or no net long-term changes to soil C stocks. Bonde et al. (1992) found that C stocks at 0 – 30 cm on an oxisol from the central Amazon decreased by 7%

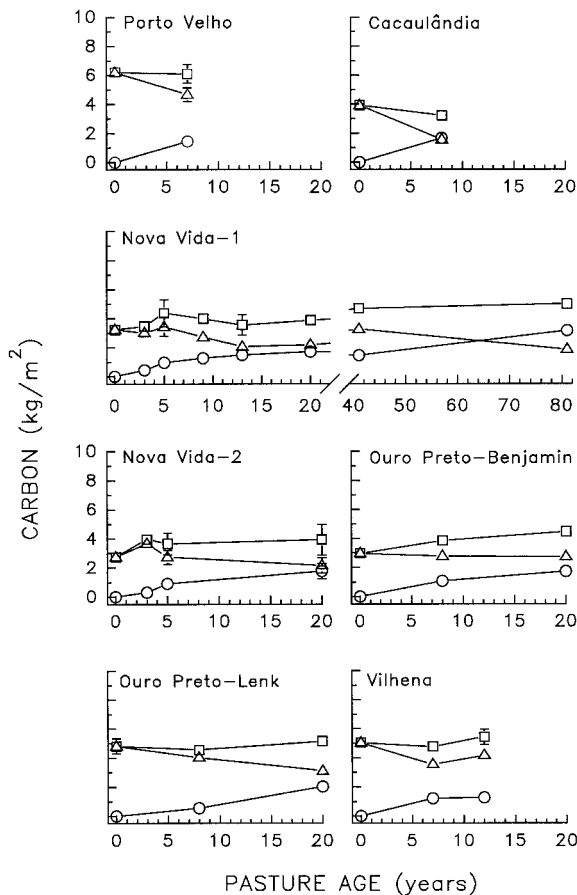


FIG. 3. Forest-derived C and pasture-derived C contributions to total soil C stocks for the top 30 cm of seven chronosequences in Rondônia. Forest- and pasture-derived C stocks were calculated from soil C concentration, soil $\delta^{13}\text{C}$, and bulk density at each depth. Symbols represent total C (\square), forest-derived C (\triangle), and pasture-derived C (\circ). Stocks were corrected for changes in the bulk density of pasture soils relative to the original forest. Error bars represent ± 1 SE and are not shown when they are smaller than the symbol.

in 2-yr-old pasture compared with the original forest but increased by 9% in 8-yr-old pasture. Also on an oxisol, Choné et al. (1991) reported a 24% decrease in C stocks to 20 cm depth in 2-yr-old pasture and an increase of 7% in 8-yr-old pasture. Eden et al. (1990) reported higher C concentrations on ultisols at a depth of 0–10 cm in both young (2–4 yr) and old pastures (6–25 yr) compared with the original forest. This variability in the response of soil C stocks to pasture formation across the Amazon probably reflects a variety of soils as well as differences in site history and pasture management. Our results from Rondônia suggest that when site history was controlled by considering only pastures formed directly after forest clearing, C accumulation was the dominant trend in pasture soils. Absence of a correlation between C and N accumulation and soil texture suggested that site history and management may be more important determinants of

the direction and magnitude of soil C change than soil type. Further evidence that management can influence carbon stocks is provided from Pará by Trumbore et al. (1995), who found lower C stocks to 10 cm depth in a degraded pasture compared with the original forest but higher C stocks in pasture managed by disking, replanting with *B. brizantha*, and fertilizing with phosphate.

Soil $\delta^{13}\text{C}$ and organic matter dynamics

Forest soil $\delta^{13}\text{C}$ values varied little across soil types and location in Rondônia and were consistent with other measurements in tropical forests both inside and outside the Amazon Basin (Choné et al. 1991, Desjardins et al. 1991, Veldkamp 1994, Trumbore et al. 1995). Similar increases in $\delta^{13}\text{C}$ values of 1–3‰ with depth occur across a broad range of tropical forests (Guillet et al. 1988, Choné et al. 1991, Desjardins et al. 1991, Trumbore et al. 1995). This pattern is also consistent with the increased $\delta^{13}\text{C}$ values that occur with depth in a broad range of temperate forest soils (Nadelhoffer and Fry 1988, Balesdent et al. 1993) and suggests that similar mechanisms control ^{13}C fractionation during decomposition.

The contribution of forest- and pasture-derived C to total soil C based on $\delta^{13}\text{C}$ values showed a general pattern of pasture C augmenting a declining pool of existing forest-derived C. In all but one location, pasture-derived C inputs approximately balanced or slightly exceeded losses of original forest-derived C. Recent evidence suggests that a similar dynamic also occurs in pastures planted in former savanna (Fisher et al. 1994). There was a range in rates of decay of the original forest-derived C at our Rondônia sites. In 7–9-yr-old pastures from seven locations, 40–93% of forest-derived C remained. In 20-yr-old pastures from four sequences, 65–92% remained. This is similar to findings reported from oxisols in Amazonas and Pará (Bonde et al. 1992, Desjardins et al. 1994); from cleared deciduous tropical forest on entisols at Chemela, Mexico (García-Oliva et al. 1994); and from cleared moist forest on inceptisols in Costa Rica (Veldkamp 1994). Trumbore et al. (1995) found that only ~16–21% of total soil C at 0–10 cm was pasture-derived in both degraded and managed 23-yr-old pastures in Pará, but a high proportion of C_3 weeds may have accounted for relatively low $\delta^{13}\text{C}$ values and low levels of C derived from pasture grasses. Significant inputs of C derived from C_3 weeds in pastures cannot be separated from the original forest C using the $\delta^{13}\text{C}$ technique.

Implications for regional C and N cycles

Carbon accumulation in the top 30 cm of the soil ranged from 1.23 to 1.77 kg/m² in those pastures that showed statistically significant increases. This potential C storage represents a 45–56% increase in total soil C, and comprises 3–12% of the C stock of the original forest vegetation. Estimates of forest biomass C in the

southwestern Amazon range from 14.2 to 40.3 kg/m² (Brown et al. 1995, Kauffman et al. 1995). Because the highest rates of C accumulation occurred in young pastures, the total future gains of soil C are limited by a lower annual rate of C sequestration in older pastures. Based on the longest chronosequence at Nova Vida, the potential for net soil C storage in the top 30 cm compared with the original forest was ~2 kg/m² in 100 yr. This represents 5–14% of total ecosystem C stocks lost due to forest clearing.

For N, changes to soil stocks that occurred following pasture creation were a considerably larger fraction of total ecosystem stocks. Significant changes to soil N stocks in Rondônia ranged from a loss of 0.25 kg/m² in 8 yr in Cacaúlândia to a gain of 0.16 kg/m² in 3 yr in Chronosequence 2 at Nova Vida. Accumulation or loss of N on the order of 0.2–0.3 kg/m² approximately equaled N stocks in aboveground vegetation lost by biomass burning (Kauffman et al. 1995). Low concentrations of NH₄⁺ and NO₃⁻ in precipitation in the Amazon Basin make it unlikely that precipitation accounts for >0.2 g N·m⁻²·yr⁻¹ (Andreae et al. 1990). Fixation of up to 100 g·m⁻²·yr⁻¹ by free-living bacteria associated with the roots of tropical pasture grasses has been reported (Döbereiner and Day 1975, Ayanaba and Dart 1977, Boddey and Victoria 1986), and could account for these increases in soil N stocks.

In this study we showed that patterns of change to soil C and N stocks were broadly similar across a range of soil types over a wide area of the southwestern Amazon Basin, and that gains of soil C and N generally outnumbered losses. Several additional pieces of information are required to assess the effect of clearing of millions of hectares for pasture on Basin-wide soil C storage. First, the direct conversion of forest to pasture is only one of a number of land-use trajectories that result in land use as pasture. Much land ends up as pasture after a period in annual crops (Sanchez 1976), and cultivation generally results in diminished soil C stocks (Sanchez et al. 1983, Vitorello et al. 1989). Second, we currently have little information from either chronosequence or chronological studies to evaluate the effects of different management practices such as grazing. Third, our estimates of maximum potential changes to soil C inventories are based only on surface soils. The presence of deep soils in the Amazon Basin creates the possibility that small changes occurring over a great depth could also comprise a substantial fraction of the total change in C stocks following land-use conversion where deep-rooted forest trees are replaced by shallow-rooted grasses (Nepstad et al. 1994, Trumbore et al. 1995).

Finally, future patterns of land use have the potential to alter the pattern and magnitude of soil C accumulation in pasture soils. High rates of forest clearing in the Amazon have left a large area of pasture that is now 10–20 yr old. The length of time land remains in pasture can influence soil C storage because the largest

changes to stocks occur typically occur during the first 10 yr after clearing. Skole et al. (1994) reported that secondary vegetation occupied 33% of the total area deforested in central Rondônia in 1989 and that clearing of secondary forests accounted for 42% of new agricultural land. This cycle of pasture abandonment and reclearing has the potential to change patterns of C accumulation and loss, either by degrading C stocks during burning or by augmenting stocks by maintaining pastures in a rapidly accumulating phase of development. We currently know little about the effects of pasture abandonment on soil C stocks, but if pastures remain abandoned for any length of time, C accumulations in aboveground plant biomass may outweigh any changes to soil stocks.

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