Oecologia (1994) 99:392–396

ORIGINAL PAPER

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Forest-to-pasture conversion influences on soil organic carbon dynamics in a tropical deciduous forest

Received: 11 March 1994 / Accepted: 14 July 1994

Abstract On a global basis, nearly 42% of tropical land area is classified as tropical deciduous forest (TDF) (Murphy and Lugo 1986). Currently, this ecosystem has very high deforestation rates; and its conversion to cattle pasture may result in losses of soil organic matter, decreases in soil fertility, and increases in CO_2 flux to the atmosphere. The soil organic matter turnover rate in a TDF after pasture conversion was estimated in Mexico by determining natural abundances of ^{13}C. Changes in these values would be induced by vegetation changes from the C_3 (forest) to the C_4 (pasture) photosynthetic pathway. The rate of loss of remnant forest-soil organic matter (fSOM) was 2.9 t ha^{-1} year^{-1} in 7-year-old pasture and decreased to 0.66 t ha^{-1} year^{-1} by year 11. For up to 3 years, net fSOM level increased in pastures; this increment can be attributed to decomposition of remnant forest roots. The sand-associated SOM fraction was the most and the silt-associated fraction the least depleted. TDF conversion to pasture results in extremely high rates of loss of remnant fSOM that are higher than any reported for any tropical forest.

Key words Tropical deciduous forest · Soil organic matter · $\delta^{13}C$ · Soil carbon fractions · Forest-to-pasture conversion

Introduction

Reports of increasing atmospheric CO_2 levels have focused research on processes controlling the global carbon cycle. Soils play an integral role in the cycling and storage of carbon (Schlesinger 1990) and the amount of organic C stored in soil is controlled by a number of factors (Jenny 1941). Land use is the most important factor. Deforestation in the tropics is responsible for an annual net release of carbon to the atmosphere. By 1985 the net release was 0.67×10^{15} g C year^{-1} from deforestation in Latin America (Houghton et al. 1991b).

In Latin America, most deforestation has been followed by conversion to pasture. By 1980, 44% of forestland had been converted to pasture (Houghton et al. 1991a), producing 42% of total C emissions (Houghton et al. 1991b). Tropical deciduous forest (TDF) represents 47% of the total forested area in Latin America, and has the highest pasture conversion rate (1.35×10^6 ha year^{-1}), with 78% of the total original area already converted to pasture (Houghton et al. 1991a).

The dominant vegetation of TDF differs in stable C isotope composition from the introduced pasture plants, which are less depleted in ^{13}C (Smith and Epstein 1971; Vogel 1980; O'Leary 1981). The soil organic carbon of forest and grassland ecosystems retains the isotopic signature of the plants (Balesdent et al. 1987; Volkoff and Cerri 1987; Kelly et al. 1991), providing a means of estimating the turnover of organic matter as a result of the conversion of forest to pasture.

The objective of this study was to estimate the rate of loss of remnant forest-soil organic matter (fSOM) in a TDF after conversion to pasture.

Materials and methods

Soil samples were taken from the hilly region of Chamela, on the Pacific Coast of Mexico (19°29′N, 105°01′W). The principal parent rocks are rhyolite and granite. The pH of the sandy-clay-loam textured entisols (USDA) ranges between 6.0 and 7.0. Illite and chlorite are the dominant clay minerals (Campo, personal communication). Soil organic matter (SOM) is concentrated in the top soil layer: 66% of total SOM is in the first 6 cm (Garcia-Oliva 1992). Mean annual temperature is 25°C and annual precipitation is 680 mm, with 80% falling from June to October (Bullock 1986). The dominant vegetation is tropical deciduous forest (Bullock and Solis-Magallanes 1990) and the forest trees are C_3 (Mooney et al. 1989). Slash-and-burn converts the forest to C_4 pastures for cattle grazing.

Soils were sampled at five sites, with time since land use conversion varying from 0 (current forest) to 1, 3, 7 and 11 years.

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Table 1 Average and (SE) of some soil characteristics from sites sampled near Chamela, Mexico

	Forest	Pasture age			
		1 year	3 years	7 years	11 years
Sand (%)	60 (2)	57 (5)	57 (5)	48 (4)	49 (4)
Clay (%)	26 (1)	22 (1)	26 (2)	29 (1)	29 (1)
pH	5.9 (0.1)	7.1 (0.1)	6.7 (0.1)	7.3 (0.1)	6.5 (0.1)

Sites had the same soil type and all the pastures belonged to one owner. Table 1 shows texture and pH of sampled sites. Three soil replicates at each site were sampled at 0–6 cm depth on the hilltop (average slope 4±2). After air drying and sieving through a 2-mm mesh, pH was measured by a glass electrode in 1:2.5 water solution, and SOM content by the Walkley-Black method (Nelson and Sommers 1982). The organic $\delta^{13}C$ analyses were conducted with whole soil, and with six soil size-fractions.

After removing plant fragments larger than 2 mm by dry sieving, 30-g soil samples were chemically dispersed by shaking overnight in 200 ml of a sodium metaphosphate solution (10 g l^{-1}). The dispersed soil was separated into coarse sands (>200 µm) and fine sands (200–50 µm) by wet sieving. The material passing the 50-mm sieve was separated into silt and clay by sedimentation. The silt fraction was separated into coarse silt (50–25 µm) and fine silt (25–2 µm) by further sedimentation. Each fraction was obtained after six successive sedimentations. The clay fraction was centrifuged and resuspended four times to optimize the separation between coarse clay (2–0.2 µm) and fine clay (<0.2 µm). The fine clay fraction was recovered after flocculation with $CaCl_2$. All fractions were oven-dried and ground in a mortar to provide a homogeneous fraction for $\delta^{13}C$ determinations.

For total-soil C determination, larger plant fragments were manually removed from 2-mm-sieved soils and smaller fragments were removed by centrifugation at 5000 rpm for 5 min. Large roots were oven-dried at 100°C for 48 h and prepared for mass spectrometric analysis. The wet root-free soil samples were oven-dried at 100°C for 48 h; a small subsample was taken for mass spectrometric determination. Litter samples were dried at 100°C to constant weight. Before mass spectrometer analysis, each sample set was finely ground for homogenization.

The ground samples were mixed with CuO and weighed into a vycor tube with quartz wool and pure Cu metal. The tubes were sealed under vacuum and burned at 850°C (Boutton 1991). The carbon dioxide was isolated and purified by cryogenic distillation on a high-vacuum manifold. The isotopic composition was measured with a Finnigan Mat 250 dual-inlet, triple-collector isotope mass spectrometer. All results are reported relative to the international V-PDB standard by calibration through NBS-19. Overall precision was 0.15‰. Total-soil $\delta^{13}C$ was analysed in the Instituto de Fisica, UNAM and replicates of total soil and size-fractions were analysed at the A&M University, Texas. Data on total-soil $\delta^{13}C$ did not differ between the two laboratories.

Values of $\delta^{13}C$ relative to that for the PDB carbonate standard are defined by the equation (Smith and Epstein 1971; Vogel 1980; O'Leary 1981):

$$\delta^{13}C=[(^{13}C/^{12}C_{\mathrm{sample}}/^{13}C/^{12}C_{\mathrm{standard}})-1]\times 10^{3} \qquad (1)$$

The percentage of SOM derived from C_4 and C_3 plants was calculated by a equation proposed by Volkoff and Cerri (1987):

$$\mathrm{pSOM}(\%)=(d-d_0/d_1-d_0)\times 100 \qquad (2)$$

Where pSOM(%) is the percentage of soil organic matter (SOM) derived from C_4 grass, d is the $\delta^{13}C$ value of the soil sampled in each plot, d_0 is the $\delta^{13}C$ value of forest soil and d_1 is the average $\delta^{13}C$ of litter from pasture (−15.3‰). The percentage of C_3 remaining in SOM (fSOM) was calculated by

$$\mathrm{fSOM}(\%)=100-\mathrm{pSOM} \qquad (3)$$

SOM contents from forest origin and pasture origin were obtained by multiplying total SOM content (t ha^{-1}) and percentage from Eqs. 2 and 3. Because bulk density increased significantly with the age of the pasture (Garcia-Oliva 1992), SOM content (t ha^{-1}) was corrected by a factor derived from the differences in soil bulk density.

Results and discussion

After slash-and-burn, SOM content increased significantly (P=0.004). The highest increment was found in 3-year-old pasture, where it was 1.3 times higher than in forest soil (Table 2). However, continuous use of pasture decreased SOM content: 11-year-old pasture had 71% of the SOM content of 3-year-old pasture (Table 2).

Litter $\delta^{13}C$ values corresponded to C_3 and C_4 plants for forest (−27.3‰) and grasses (−15.7‰), respectively (Table 2). In the forest plot, the differences between litter and roots were negligible, and the values were similar to those reported for forest trees, shrubs and vines at Chamela by Mooney et al. (1989). SOM was enriched in ^{13}C by 1.5‰ in relation to litter and roots due to decomposition processes. Such an enrichment has been reported by several authors (O'Brien and Stout 1978; Balesdent et al. 1987; Natelhoffer and Fry 1988).

For up to 3 years after slash-and-burn, net remnant fSOM levels increased in pastures reaching values 17% higher than forest soil (Fig. 1). This increment in fSOM can be attributed to decomposition of remnant forest roots. The root:shoot biomass ratio of this TDF is 0.42, which is substantially higher than in most tropical moist forests (Castellanos et al. 1991). Roots in a 1-year-old pasture had $\delta^{13}C$ values representative of the forest (−25‰) but not of C_4 grasses (Table 2). In 7-year-old pasture, the $\delta^{13}C$ value of roots was a mixture of C_3 and C_4 plants (−19.9‰), suggesting that remnant forest roots were present in the pasture for up to 7 years after slash-and-burn. These changes were reflected in the $\delta^{13}C$ of total SOM, which was significantly greater in the 7-year-old pasture than in the forest (Table 2). The increase of soil organic matter from pasture (pSOM) may compensate for the loss of fSOM (Fig. 1).

The fSOM was lowest in the 11-year-old pastures, where fSOM made up only 45% of the total SOM (Fig. 1). The rate of loss of fSOM changed substantially over time, with the most rapid loss in year 1 and year 3, followed by an exponential decrease due to differential loss rates of the remaining material (Melillo et al. 1989). The estimated loss rate of fSOM was 2.9 t ha^{-1} $year^{-1}$ in 7-year-old pasture and decreased to 0.66 t ha^{-1} $year^{-1}$ by

Table 2 Average and (SE) of total soil organic matter (SOM) $\delta^{13}C$ ratios (‰) and total SOM content (t ha^{-1}) of the top 0–6 cm soil near Chamela, Mexico. The *letters* represent groups given by Tukey test at P=0.05

	Forest	Pasture age			
		1 year	3 years	7 years	11 years
SOM content	21.2^{C}	23.9^{B}	27.9^{A}	18.5^{C}	19.8^{C}
$\delta^{13}C$	–25.8^{A} (0.29)	–24.8^{AB} (0.07)	–25.0^{AB} (0.35)	–23.4^{B} (0.46)	–21.4^{C} (0.61)
Litter	–27.3	–15.7	–13.5	–15.4	–15.9
Roots	–27.6	–25.2	n.d.	–19.9	n.d.

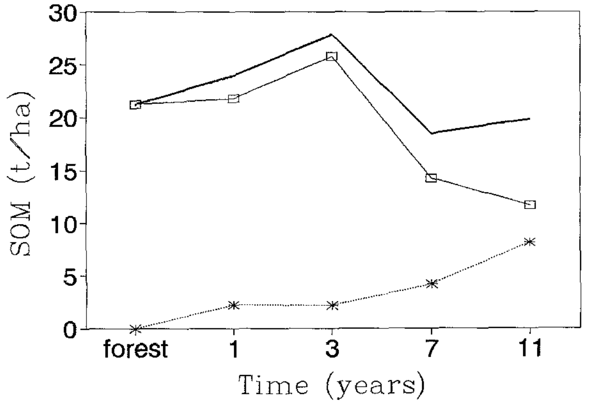

Fig. 1 Soil organic matter (SOM) (0–6 cm depth) of forest origin (*squares, lighter line*) and of pasture origin (*asterisks, dotted line*), and total (*heavy line*), in intact tropical deciduous forest and in pastures of varying ages near Chamela, Mexico

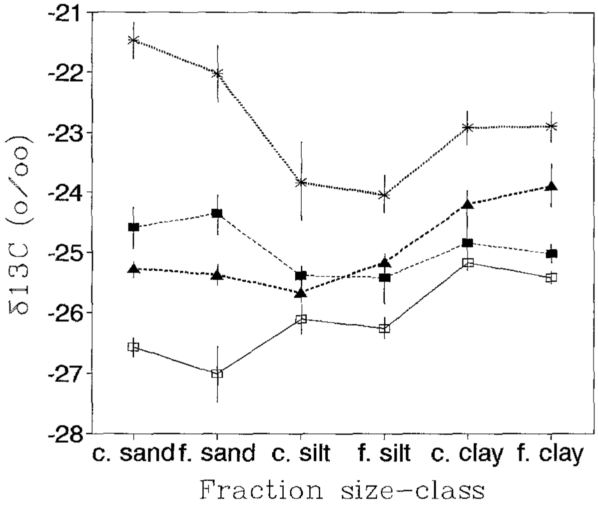

Fig. 2 Soil organic matter $\delta^{13}C$ ratios (‰) ±SE for six size-fractions of 0–6 cm depth in intact tropical deciduous forest and in pastures of varying ages near Chamela, Mexico (*open squares* forest, *solid triangles* 1-year-old pasture, *solid squares* 3-year-old pasture, *asterisks* 7-year-old pasture)

year 11. These loss rates are much higher than reported in previous studies (Vitorello et al. 1989; Cerri et al. 1991). Assuming exponential decay, the half-life of fSOM is 6.8 years at the outset and "increases" to 20 years in the 11-year-old pasture, as only the most recalcitrant fSOM remains.

In forest soil, clay-associated organic matter was richer in ^{13}C than in whole soil (Fig. 2). Respired CO_2 would have been depleted in ^{13}C, whereas derived microbial products become richer in ^{13}C (Smejkal et al. 1971). As a result, the fine-clay-associated fraction is probably mostly attributable to microbial metabolites (McGill et al. 1975; Anderson et al. 1981; Ahmed and Oades 1984). In contrast, sand-associated organic matter was closer to litter and root $\delta^{13}C$ values (Fig. 2), suggesting that the sand-associated fraction is composed of less processed material (Anderson et al. 1981; Christensen 1992; Balesdent et al. 1987; Bonde et al. 1992).

Each soil size-fraction had a different loss rate, and the sand-associated fraction had the highest depletion (Table 3). Moreover, the sand-associated fraction had a higher loss rate than non-fractionated soil. For 7-year-old pastures, fSOMs were 77% and 55% for whole soil and the sand fraction, respectively. Martin et al. (1990) suggest that this fraction has a half-life of <10 years.

The silt-associated fraction had slower loss rate than clay-associated fractions (Table 3). Percentage fSOMs in silt and clay were 70 and 76%, respectively. Considerable redistribution of SOM among size fractions could be shown, while no net changes for the total SOM were observed (Tiessen et al. 1982). The redistribution of SOM from labile fractions to more humified fractions has been demonstrated by other authors (Ladd et al. 1977; Anderson et al. 1981).

It is interesting that the three finest fractions, principally fine clay, increased in fSOM from 1-year-old to 3-year-old pastures (Table 3). This result suggests a high decomposition rate of remnant dead roots by microorganisms. In general, the mineralization rate of SOM increases as particle size decreases, and clay-associated SOM shows higher enrichment than other fractions (Christensen 1992; Christensen and Sorensen 1985). Although, the clay-associated fraction had lower fSOM than the silt fraction in 7-year-old pasture (Fig. 2), Gregorich et al. (1991) found that clay from sandier soils became relatively more enriched in new SOM than clay isolated from heavier soils, and clay SOM formed during the initial and rapid decomposition phase is less resistant to further turnover in sandy soils. Van Veen et al. (1985) hypothesized that in finer-textured soils relatively more products released from dead cells are retained in the vicinity of other surviving bacteria than in coarse-textured soils. This suggests that sandy soils may be less efficient in stabilizing new SOM than soils richer in clay (Christensen 1992).

Table 3 Percentages of soil organic matter from forest (fSOM) for different size-fractions of the top 0–6 cm soil near Chamela, Mexico

Fraction Size	Forest	1 year	3 years	7 years
Coarse sand >200 μm	1.00	0.89	0.83	0.55
Fine sand 200–50 μm	1.00	0.86	0.77	0.58
Coarse silt 50–25 μm	1.00	0.96	0.93	0.79
Fine silt 25–2 μm	1.00	0.90	0.93	0.80
Coarse clay 2–0.2 μm	1.00	0.90	0.96	0.77
Fine clay <0.2 μm	1.00	0.85	0.96	0.75

Since mineral-associated organic matter has been shown to have relatively low nutrient availability (Anderson et al. 1981; Tiessen and Stewart 1983), land use changes not only reduce total SOM content of soil, but also reduce nutrient availability (Cambardella and Elliot 1992). The combined effects of cattle ranching associated with intensive and repeated fires will ultimately result in severe reduction in long-term site productivity.

Acknowledgements We thank D. Binkley, G. Kelly and R. Sanford Jr. for helpful comments on the manuscript; Thomas Boutton for the use of facilities for fractionation and $\delta^{13}C$ analysis in his laboratory (A&M University, Texas); the personnel of the Chamela Biological Station, Universidad Nacional Autónoma de México, for logistic support during field work; Enrique Solís and Edith Cienfuegos for laboratory assistance. This study was supported by DGAPA-UNAM, Mexico, and conducted as part of a research program on tropical deciduous forest at the Centro de Ecología, UNAM, México.

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