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Carbon-13 variation with depth in soils of Brazil and climate change during the Quaternary

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Abstract Paleoecological and geomorphological studies indicate that, during the middle Holocene, there was a predominance of drier conditions with grassy savannahs replacing forests across the South American continent. Modern savannahs are composed mainly of C4 plants and soils developed under this type of vegetation show enrichment in ^{13}C compared to soils under C3 vegetation cover. If soils contain stabilized organic matter formed in the middle Holocene, we hypothesize that former C4 vegetation would be evidenced by a large enrichment of ^{13}C in soil organic matter (SOM). We investigate this possibility examining the depth variation of carbon isotopic composition in 21 soil profiles collected by different researchers at 14 different sites in Brazil. Of these, profiles from only three sites showed a marked increase of ^{13}C with depth (9–10‰ enrichment in $\delta^{13}\text{C}$ difference between the surface soil and deepest depth); two sites showed intermediate enrichment (4–5‰), and nine sites showed a small enrichment of approximately 2.5‰. The majority of sites showing all-C3 derived SOM were in the Amazon region. Possible causes for the absence of a large ^{13}C enrichment with depth are: (1) dominance of C3 rather than C4 grasses in mid-Holocene savannahs, (2) soil profiles did not preserve organic matter derived from mid-Holocene plants, (3) the retreat of forest areas did not occur on a regional scale, but was a much more localized phenomenon.

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Introduction

Soil organic matter (SOM) is a complex mixture of compounds from different pools, ranging from very labile compounds with very fast cycling times to refractory components that accumulate over millenia (Trumbore 1993). These attributes are susceptible to climate change, which can cause alterations in organic matter inputs and rates of decomposition (Jenkinson et al. 1991). The cumulative response of SOM behavior to past and future changes is a significant factor in the global carbon cycle (Prentice and Fung 1990; Tans et al. 1990; Jenkinson et al. 1991).

Paleoecological and geomorphological studies suggest the occurrence of severe climatic changes in the South American continent. It has been hypothesized that there were drier periods during the Pleistocene and Holocene than the present, when the tropical forest was replaced by savannah-like vegetation, with predominance of grasses (Van der Hammen 1974; Absy and Van der Hammen 1976; Absy 1980; Ab'Saber 1982; Bigarella and Andrade-Lima 1982; Leyden 1985; Markgraf 1989; Bush et al. 1990; Bush and Colinvaux 1990; Markgraf 1991; Absy et al. 1991). The maximum in the proportion of grass pollen was found in the middle Holocene from ca. 6,000 to 4,000 years before present (BP) for several places in South America (Absy 1980; Servant et al. 1989; Markgraf 1989; Absy et al. 1991; Ledru 1992, 1993; Servant et al. 1993), from 10,500 to 10,400 years BP for central Brazil (Servant et al. 1989, 1993; Ledru 1993), and ca. 13,000 years BP for eastern Amazonia (Absy et al. 1991).

If these grasses were of the C4 type, it may be possible to find a residual isotopic signal preserved in soil profiles. Depending on the degree of ^{13}C enrichment in SOM with depth, two basic processes could explain the observed trends

1. If the ¹³C enrichment with depth is small, the decomposition of organic matter, which favors ¹²C, is most likely the cause of the trend.

2. If the ¹³C enrichment with depth is large, it is a stronger indication that the signal is due to the previous existence of ¹³C-enriched vegetation, probably C4 grasses.

We explore those possibilities through the analyses of the stable carbon isotope composition of 21 soil profiles collected at 14 sites in Brazil, encompassing different soil types and climatic conditions (Volkoff et al. 1982; Desjardins et al. 1991; Valencia 1993; Pessenda et al. 1995; Trumbore et al. 1995). Radiocarbon data for the organic matter from the same soil profiles provide an estimate of the minimum age of stabilized C4 organic matter.

Methods

Locations of soil profiles are shown in Fig. 1. A total of 21 soil profiles at 14 sites, encompassing different climate regimes and soil types were collected (Table 1). Of these sites 7 were located in

the Amazon basin, which is characterized by high temperature and heavy rainfall (Fig. 1). Three other profiles were also collected in areas of high average temperatures: Juacema, Nhecolândia and Salitre. The first one is located in the northeast region of Brazil, which is mainly characterized by low rainfall (Fig. 1). The Nhecolândia profile was collected in the Brazilian Pantanal, one of the largest floodplains in the world, and the Salitre profile was collected in the southernmost region of Brazil (Fig. 1). In areas of lower average temperatures, six profiles in four different places (São Roque, Piracicaba, Londrina and Tunas) were collected (Fig. 1). Soil types differed among places (Table 1). The most common soil types in Brazil, *Latosso* and *Podzólico*, which are equivalent to ultisols and oxisols in the American classification system, were present at most sampling sites (Table 1). Soils classified as *Terra Roxa Estruturada* (equivalent to alfisols) were present at two sites, and finally *Cambissolo* and *Areia Quartzosa*, both equivalent to inceptisols, were present at one site each. In all sampling sites the vegetation was the primary forest characteristic of each region.

Details of soil sampling and soil characteristics can be found elsewhere (Cerri 1979; Volkoff et al. 1982; Soubiès and Chauvel 1985; Martins et al. 1991; Higa 1989; Rocha 1990; Valencia 1993; Pessenda et al. 1996; Trumbore et al. 1995). Analysis of carbon isotopic composition, expressed as δ¹³C, were not always carried out by the same authors that collected soil samples. (A list of those authors can be found in Table 1.) Radiocarbon ages, expressed as years before present (years BP), were available for profiles located at Piracicaba, Londrina, Altamira, Salitre, Nhecolândia and Para-

Fig. 1 Upper panel map of Brazil showing the geographical location of soil profiles. Stars indicate sites where the variation with depth of Δ¹³C values of soil organic matter clearly indicates the existence of previous C4 vegetation. Circles indicate sites with no trends. Squares indicate sites with equivocal Δ¹³C trends. Lower panel annual average temperature and average rainfall of sample sites

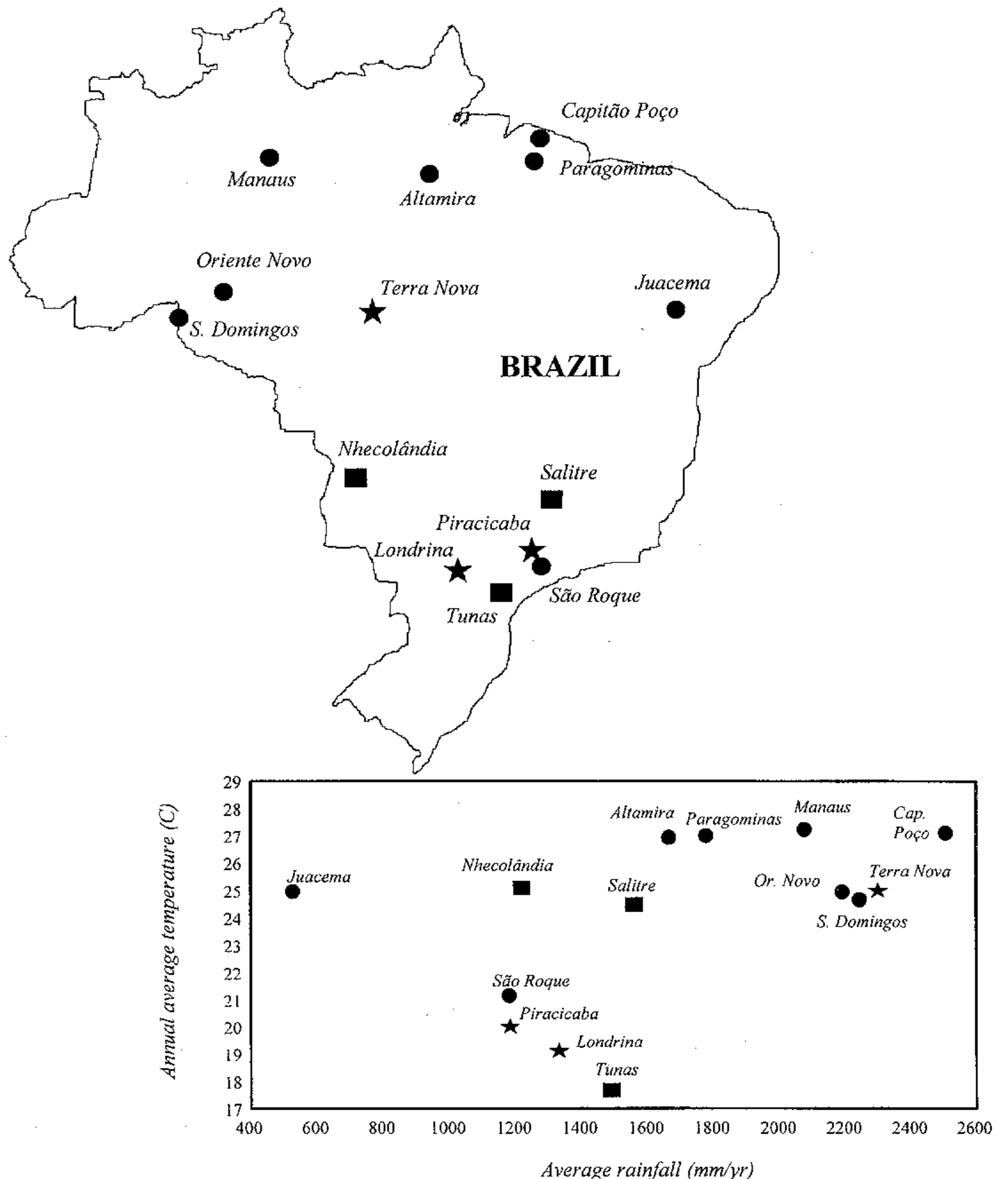


Table 1 Sites of soil sampling (*numbers in parentheses* indicate the number of profiles collected at each site) following by soil type according to the Brazilian classification system; soil texture; mean annual temperature, rainfall and climate type

Code – Site	Brazilian classification	Texture	Mean annual temperature	Mean annual rainfall	Climate	References
Man – Manaus (1)	Latossolo Amarelo	Clay	27° C	2100 mm	Trop. humid	a
Alt – Altamira (2)	Terra Roxa Estruturada	Clay	27° C	1650 mm	Trop. humid	b, c, d
Cpo-Capitão Poço (1)	Latossolo Podzolisado	Silty-clay	27° C	2500 mm	Trop. humid	e, c
Par – Paragominas (3)	Latossolo Amarelo	Clay	27° C	1750 mm	Trop. humid	f
Ori – Oriente Novo (1)	Latossolo Vermelho-Amarelo	Silty-clay	25° C	2200 mm	Trop. humid	g, c
Dom – S. Domingos (1)	Podzólico Vermelho-Amarelo	Silty-clay	25° C	2200 mm	Trop. humid	g, c
Ten – Terra Nova (1)	Cambissolo	Silty-clay	25° C	2300 mm	Trop. humid	h, c
Jua-Juacema (1)	Latossolo	Silty-clay	25° C	500–1000 mm	Trop. semi-arid	g, c
Pan – Nhecolândia (1)	Areia Quartzosa	Sandy	25° C	1280 mm	Trop. humid	i
Sal – Salitre (2)	Latossolo Vermelho-Amarelo	Clay	24° C	1700 mm	Subtropical	j
Sro – São Roque (1)	Podzólico	Sandy-clay	21° C	1200 mm	Subtropical	g, c
Pir – Piracicaba (2)	Latossolo Vermelho-Amarelo	Clay	20° C	1200 mm	Suptropical	d, g
Lon – Londrina (2)	Terra Roxa Estruturada	Clay	19° C	1250 mm	Suptropical	d, g
Tun – Tunas (1)	Latossolo Podzolisado	Silty-clay	18° C	1400 mm	Temperate	g, c

^a Volkoff et al. (1982) soil description and $\delta^{13}\text{C}$ analysis

^b Rocha (1990) soil description

^c Desjardins et al. (1991) $\delta^{13}\text{C}$ analysis

^d Valencia (1993) $\delta^{13}\text{C}$ analysis

^e Martins et al. (1986) soil description

^f Trumbore et al. (1995) soil description and $\delta^{13}\text{C}$ analysis

^g Cerri (1979) soil description

^h Higa (1989) soil description

ⁱ Victoria et al. (1995) soil description and $\delta^{13}\text{C}$ analysis

^j Pessenda et al. (1996) soil description and $\delta^{13}\text{C}$ analysis

gominas and these analyses were conducted by Valencia (1993) for the first three profiles, and by Pessenda et al. (1996), Victoria et al. (1995), and Trumbore et al. (1995) for the three last profiles, respectively.

Results and discussion

The contemporary vegetation cover of all sites was primary forest (C3 plant type), and the $\delta^{13}\text{C}$ of the surface soil organic matter varies from -28.5 to 26.0‰ . In order to make the comparison among different profiles easier, the depth variability of the carbon isotopic composition in each profile was expressed as the difference of the $\delta^{13}\text{C}$ of a soil depth in relation to the $\delta^{13}\text{C}$ value of the most superficial sampling depth. We call this difference $\Delta^{13}\text{C}$, defined as:

$$\Delta^{13}\text{C} = \delta^{13}\text{C}_{\text{depth}} - \delta^{13}\text{C}_{\text{surface}}$$

where $\delta^{13}\text{C}_{\text{surface}}$ is the value of the surface soil and $\delta^{13}\text{C}_{\text{depth}}$ is the value at a given depth. $\Delta^{13}\text{C}$ values were mostly positive, reflecting the fact that $\delta^{13}\text{C}$ values increased with depth in nearly all soil profiles.

Results were grouped according to the $\Delta^{13}\text{C}$ values. Figure 2A and B shows profiles with the smallest $\Delta^{13}\text{C}$ values. The profiles with the highest $\Delta^{13}\text{C}$ are shown in Fig. 2D and profiles with intermediate to small values of $\Delta^{13}\text{C}$ are grouped in Fig. 2C.

Most of the soil profiles with the smallest $\Delta^{13}\text{C}$ values (Fig. 2A and 2B) are from the Amazon Basin (Fig. 1). In these profiles the highest $\Delta^{13}\text{C}$ value was 3.5‰ , but most of the values were smaller than 2.5‰ , which indicates that the major cause of ^{13}C enrichment with depth was probably fractionation during decomposition of SOM. The only exception to this pattern was the depth variability observed in the Terra Nova profile, where the $\Delta^{13}\text{C}$

value reached almost 8.5‰ near the bottom (Fig. 2D). Profiles from Piracicaba and Londrina showed similar ^{13}C enrichment (Fig. 1). The profile Lon-1 at Londrina reached a $\Delta^{13}\text{C}$ value of 11.5‰ at the bottom (Fig. 2D). In such cases the most likely cause for this large ^{13}C enrichment with depth is the existence of prior C4 vegetation (Dzurec et al. 1985; Mondenesi et al. 1986; Schwartz et al. 1987; Volkoff and Cerri 1987; Martin et al. 1990; Desjardins et al. 1991; McPherson et al. 1993; Wang et al. 1993; Mariotti and Peterschmitt 1994; Victoria et al. 1995). Both profiles of Salitre, Nhecolândia, and Tunas had intermediate $\Delta^{13}\text{C}$ values varying approximately from 4.0 to 6.0‰ (Fig. 2C). The Nhecolândia profile came from the Brazilian Pantanal, a large floodplain, highly dynamic in terms of geomorphology (Adamoli 1982), with a landscape that alternates high land forested areas with low land areas of savannah. This dynamism is reflected in the $\Delta^{13}\text{C}$ values, with reach a maximum of almost 6‰ at 100 cm depth, suggesting the replacement of the forest by a C4 savannah, and a decrease to almost 0.5‰ at 170 cm depth, indicating the dominance of a C3 vegetation type again (Victoria et al. 1995). The profiles from Tunas and Salitre (Sal-1 and Sal-2) show $\Delta^{13}\text{C}$ increasing from 4.0 to 6.0‰ , within the upper 30 cm. Below, $\Delta^{13}\text{C}$ values were constant to the bottom of the profiles. According to Pessenda et al. (1995) the cause of the increase of $\Delta^{13}\text{C}$ with depth at these sites is fractionation of isotopes during decomposition and not a past vegetation change. However, palynological evidence of a past vegetation change in favor of grasses that may have been C4 (Ledru 1993), and the $\Delta^{13}\text{C}$ value of 4.0 – 6.0‰ , suggest that paleovegetation change cannot be ruled out as an explanation.

Table 2 summarizes the radiocarbon ages of soil profiles for those where such data were available. The ^{14}C

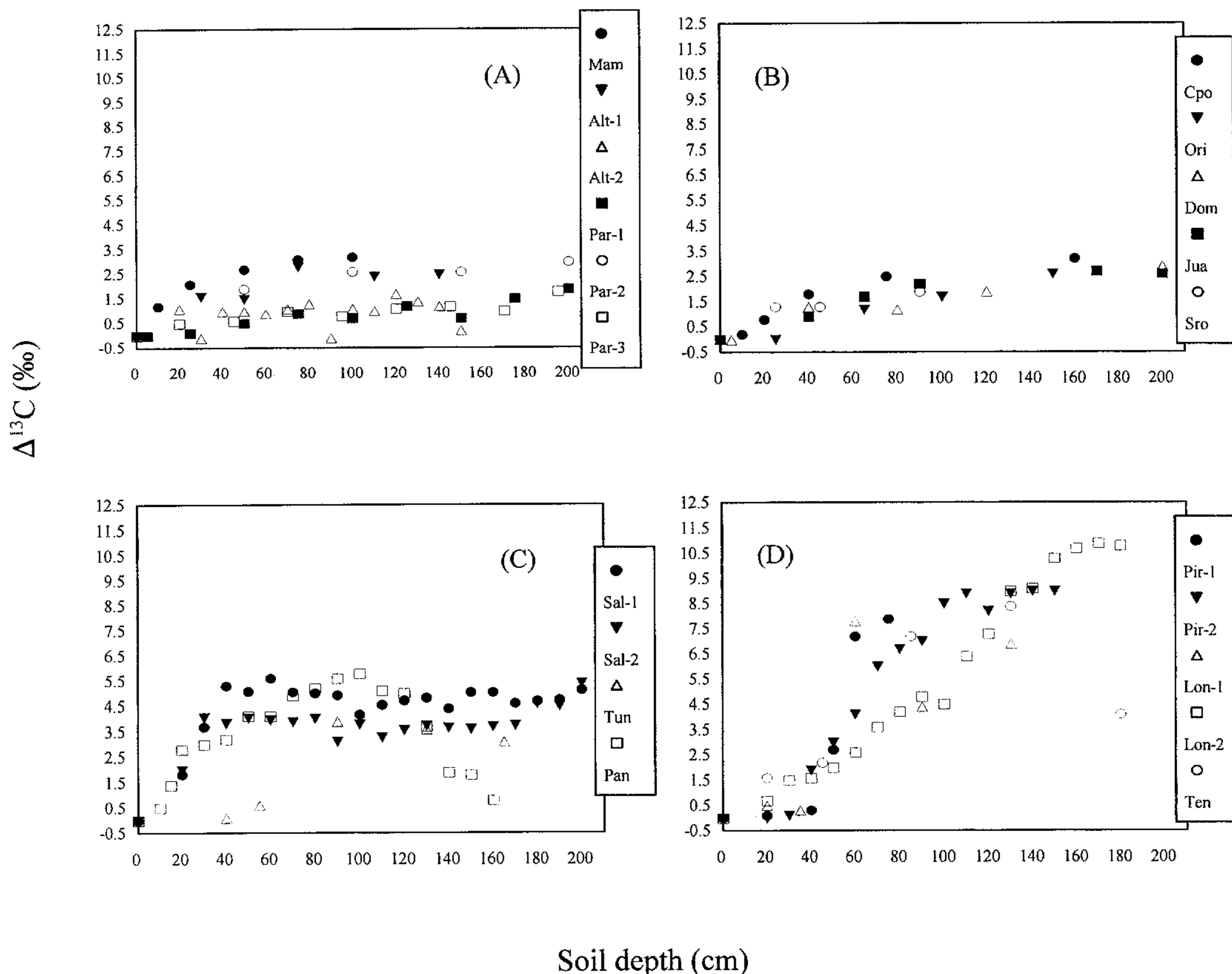


Fig. 2 Variation of $\Delta^{13}C$ values in relation to soil depth: **A, B** sites with smallest $\Delta^{13}C$ values; **C** sites with intermediate $\Delta^{13}C$ values, and **D** sites with highest $\Delta^{13}C$ values. Site abbreviations are given in Table 1

ages reported represent the average “age” of a carbon atom in SOM, and certainly represent a mixture of both older and younger material. For samples from deep in the soil, the radiocarbon age may be taken as a minimum age for stabilized organic matter. For instance, although the ^{14}C age of organic matter at 100 cm depth in Paragominas soils is about 14,000 years BP, it was estimated by Trumbore et al. (1995) that this average age represents a mixture of 10% modern carbon with 90% radiocarbon-free carbon (i.e., 90% with average age >40,000 years BP).

One of the most widely accepted climatic changes in the past is the drought that occurred in the middle Holocene (Servant et al. 1993). Pollen records from Salitre (Ledru 1993) and Southern Serra dos Carajás, near Altamira (Absy et al. 1991) show sharp increase in grass species. The Piracicaba, Londrina and Terra Nova profiles clearly show a sharp increase in $\Delta^{13}C$ (Fig. 2C). The deepest dated depths (170–180 cm) in the Piracicaba and Lond-

rina profiles reach ages of ca. 3600 years BP and ca. 9300 years BP. These soils were presumably subjected to paleoclimatic and paleovegetation changes associated with the mid-Holocene. In Salitre the deepest dated depth (190–200 cm) is almost 7000 years BP, which means that these profiles also experienced the middle Holocene drought. However, the increase of $\Delta^{13}C$ with depth was not as sharp as in the Piracicaba and Londrina profiles, making it difficult to establish the cause for this increase. No other profiles showed the effects of the middle Holocene dryness in their carbon isotopic composition. In addition, seven other profiles collected in several areas of the Amazon region down to 4 m depth show no significant variation in carbon stable isotopic composition (Sanaiotti, unpublished work). As modern savannah soils clearly show the presence of C4 grasses in their SOM (Dzurec et al. 1985; Mondenesi et al. 1982; Schwartz et al. 1987; Volkoff and Cerri 1987; Martin et al. 1990; Desjardins et al. 1991; McPherson et al. 1993; Wang et al. 1993; Mariotti and Peterschmitt 1994), the apparent absence of C4 signal in majority of the profiles is intriguing.

There are several hypothesis that can explain the lack of a C4 signal.

Table 2 Radiocarbon ages (years BP) of soil organic matter along some soil profiles

Depth (cm)	Altamira ^a Alt-2	Paragominas ^b Par-1	Nhecolândia ^c	Salitre ^d Sal-2	Piracicaba ^a Pir-2	Londrina ^a Lon-2
0–10	modern	modern	modern	240	modern	modern
20–30		2400				
30–40			modern			
40–50	1440	4850			1230	820
70–80	2790		639		2680	1920
90–100	3640	14190		3700	3030	2390
110–120			1483			
120–130	4800				3260	5450
150–160				5550		
160–170			2002			
170–180	4390				3640	9340
190–200				6940		
290–300		22470				

^a Valencia (1993); ^b Trumbore et al. (1995); ^c Victoria et al. (1995); ^d Boulet et al. (1995)

1. The lack of signal would be consistent with dominance by C3 rather than C4 grasses. The same hypothesis was raised by Guillet et al. (1988), who found a similar situation in the tropical region of Colombia. However, judging by the modern savannahs of the world, this is unlikely.

2. The retreat of forest areas was not on a regional scale, but was a much more localized phenomenon.

3. The C4 plants were not present long enough to leave their isotopic imprint on stabilized soil organic matter.

The refuge theory for the high degree of biodiversity in tropical South America suggests that the high diversity resulted from differential species evolution in forest patches that were isolated when forests were replaced with grassy savannahs during the Pleistocene and Holocene, and remained isolated until a new climatic change provoked the return of an intact continuous forest (Haffer 1969; Vanzolini 1970; Prance 1973, 1982; Brown 1974). If the findings of this study are confirmed in further analysis, it would be a strong indication that extensive areas of grass never existed in the Amazon, especially during the Holocene. In view of refuge theory this would have strong implications for interpretations of species evolution of the Amazon rain forest.

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