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Vegetation dynamics during the late Pleistocene in the Barreirinhas region, Maranhão State, northeastern Brazil, based on carbon isotopes in soil organic matter

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Abstract

The study place is in the Barreirinhas region, Maranhão State, northeastern Brazil. A vegetation transect of 78 km was studied among four vegetation types: Restinga (coastal vegetation), Cerrado (woody savanna), Cerradão (dense woody savanna), and Forest, as well as three forested sites around Lagoa do Caçó, located approximately 10 km of the transect. Soil profiles in this transect were sampled for $\delta^{13}C$ analysis, as well as buried charcoal fragments were used for ^{14}C dating. The data interpretation indicated that approximately between 15,000 and ~9000 ^{14}C yr B.P., arboreal vegetation prevailed in the whole transect, probably due to the presence of a humid climate. Approximately between ~9000 and 4000–3000 ^{14}C yr B.P., there was the expansion of the savanna, probably related to the presence of drier climate. From ~4000–3000 ^{14}C yr B.P. to the present, the results indicated an increase in the arboreal density in the area, due to the return to a more humid and probably similar climate to the present. The presence of buried charcoal fragments in several soil depths suggested the occurrence of palaeofires during the Holocene. The vegetation dynamic inferred in this study for northeastern Brazil is in agreement with the results obtained in areas of Amazon region, based on pollen analysis of lake sediments and carbon isotope analysis of soil organic matter (SOM), implying than similar climatic conditions have affected these areas during the late Pleistocene until the present.

Keywords: Barreirinhas region; Carbon isotopes; Soil organic matter

Introduction

Most of the studies on palaeoenvironmental reconstruction during the late Quaternary and the Holocene in Brazil have been based on pollen records. The regions investigated included the Amazon (Behling and Costa, 2000; Bush et al., 2000; Colinvaux et al., 1996; Sifeddine et al., 2001; Van der Hammen and Absy, 1994), central (Salgado-Labouriau et al., 1997), southeastern (Behling et al., 1998) and south regions of Brazil (Behling, 1995; Roth and Lorscheitter, 1993). Carbon isotopes techniques in SOM have also been applied to reconstruct palaeovegetation changes in south (Pessenda et al., 1996a), southeastern (Gouveia et al., 2002; Pessenda et al., 1996a, 2004), central (Pessenda et al., 1996b), and northern region of Brazil (Freitas et al., 2001; Pessenda et al., 1998a, 1998b, 2001a).

The application of carbon isotopes is based on the different ^{13}C composition of C_3 (trees) and C_4 (grasses) plants and its preservation in SOM. $\delta^{13}C$ values of C_3 plants

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range from approximately −32‰ to −20‰ PDB, with a mean of −27‰. In contrast, δ^{13}C values of C_4 species range from −17‰ to −9‰, with a mean of −13‰. Thus, C_3 and C_4 plant species have distinct δ^{13}C values and differ from each other by approximately 14‰ (Boutton, 1996). The use of ^{14}C dating in the SOM (humin fraction) and/or in the buried charcoal fragments in the soil (Pessenda et al., 1996a, 1996b, 1998a, 1998b, 2001b, 2004) establish the chronology of the events. The carbon isotope approach for identification and changing distribution of C_3 and C_4 plant communities (i.e., forest vs. savanna vegetation) and inferences related to humid and drier paleoclimatic conditions, respectively, have been applied on regional studies from the Amazon basin to the southern region of Brazil and elsewhere (e.g., Boutton, 1996; Desjardins et al., 1996; Freitas et al., 2001; Gouveia et al., 2002; Pessenda et al., 1996a, 1996b, 1998a, 1998b, 2001a, 2004).

Recent efforts for paleoclimatic reconstruction in Brazil have focused in the NE region, because of its importance for a better understanding the history of neotropics (Absy et al., 1991; Behling and Hooghiemstra, 2001; Colinvaux et al., 1996; Ledru et al., 1996; Martin et al., 1997) and its biogeographic status, concerning the origin and past floristic connections with the Amazon and Atlantic rainforest regions (Andrade-Lima, 1982; Prance, 1985). Few studies have been developed in this region, probably due to the scarcity of stable and perennial lakes and the occurrence of strong droughts (Nimer, 1989) that can destroy pollen in lacustrine deposits (Behling et al., 2000). One of these studies carried out in the Icatu river valley in the semiarid region of Bahia State documented vegetation and climate changes during the last 11,000 ^{14}C yr B.P. (De Oliveira et al., 1999), with a humid and cold period during the early Holocene, which become progressively drier during the Holocene. Other studies based on pollen data collected in marine sediment from the upper continental slope of NE Brazil (Behling et al., 2000) and at Lagoa do Caçó, Maranhão State (Ledru et al., 2001, 2002), suggests a late-glacial increase of moist climatic conditions. In the beginning of Holocene, the vegetation was opened and scarce, changing progressively toward a woody savanna (Behling et al., 2000; Ledru et al., 2002). A molecular fossil (onocerane I) detected in the sediment of Lagoa do Caçó suggested a strong aridity at the beginning of the Holocene (Jacob et al., 2004a). From the early to mid-Holocene, the Lagoa do Caçó level rose gradually despite the lower moisture availability and a distinct dry period until 7000 cal yr (Sifeddine et al., 2003), which correspond to ca. 6000 ^{14}C yr B.P. Microscopic charcoal fragments were found in this site in this period (Ledru et al., 2001), indicating that the increase of humidity was interrupted by dry phases. The very wet late glacial period was related to the annual movement of the Inter-Tropical Convergence Zone (ITCZ) over northeastern Brazil, the strong influence of the Antarctic cold fronts and changes of the high-pressure cell over the southern Atlantic (Behling et al., 2000), followed by a strong precession signal that induced a strong impact on the seasonality in the tropics (Ledru et al., 1998; Martin et al., 1997).

In this paper, we present the first comprehensive carbon isotope record of vegetation dynamics in the NE Brazil, covering approximately the last 15,000 ^{14}C yr B.P. (late Pleistocene and Holocene). This record was obtained in soil samples collected along a 78-km transect across restinga, savanna, and semidecidous forest ecosystems, and in three forested points located approximately 10 km northwest of the transect (Ribeiro, 2002). This region is located at the southernmost limit of seasonal displacement of the ITCZ, near the Atlantic ocean and on the border of Amazon Basin (Jacob et al., 2004b; Ledru et al., 2002; Sifeddine et al., 2003), a strategic area to record palaeoenvironmental (climate and vegetation) changes that occurred in the South America continent.

Study area and vegetation

The study site is in northeastern Brazil (2°52′ S/45°55′ W and 3°11′ S/43°22′ W, 100–120 m.a.s.l) (Fig. 1). The mean annual temperature is around 26°C and the mean annual precipitation is in the range of 1500–1750 mm. The regional climate is tropical semihumid, characterized by a 6-month rainy season from December to May (Nimer, 1989). The 78-km transect is located from the coordinate 2°52′ S/45°55′ W (km 15) to 3°11′ S/43°22′ W (km 78), along the road between the cities of Barreirinhas (referred as km 0) and Urbano Santos (Fig. 1). The sampling sites are denominated F15, C17, C20, C25, F46, C54, and C78 (F = Forest, C = Cerrado, and the numbers represent km). F16 and C16 are transition sites. In addition, three forested sites denominated LCF50, LCF150, and LCF 200, are located 50, 150, and 200 m, respectively, from the border of Lagoa do Caçó (2°58′ S/43°25′ W), situated approximately 10 km northwest of the transect from km 54 location.

The km 15 is covered by “Restinga,” the coastal vegetation encountered on the dunes and include small trees, shrubs [*Byrsonima* spp. (Malpighiaceae), *Copaifera* spp. (Caesalpiniaceae), *Hymenaea* sp. (Fabaceae), *Caryocar coriaceum* (Caryocaraceae)], and many Bromeliaceae, being the dominant herbaceous plant *Chamaecrysta flexuosa* (Fabaceae) (Ledru et al., 2002; Ribeiro, 2002). In km 78, the vegetation cover is “Cerradão,” a forested formation with trees up to 15-m high, without a shrubby understorey but with a herbaceous stratum in tufts (Coutinho, 1990). Arboreal species such as *Curatella americana*, *Qualea grandiflora*, *Q. parviflora*, *Caryocar brasiliense*, *Bowdichia virgilioides*, and *Stryphnodendron barbatiman* are typical of this formation. The point F46, covered by a semideciduous forest, is located approximately 10 km southeast of the transect at a point close to location C54. The sandy “Cerrado” savanna vegetation is located between

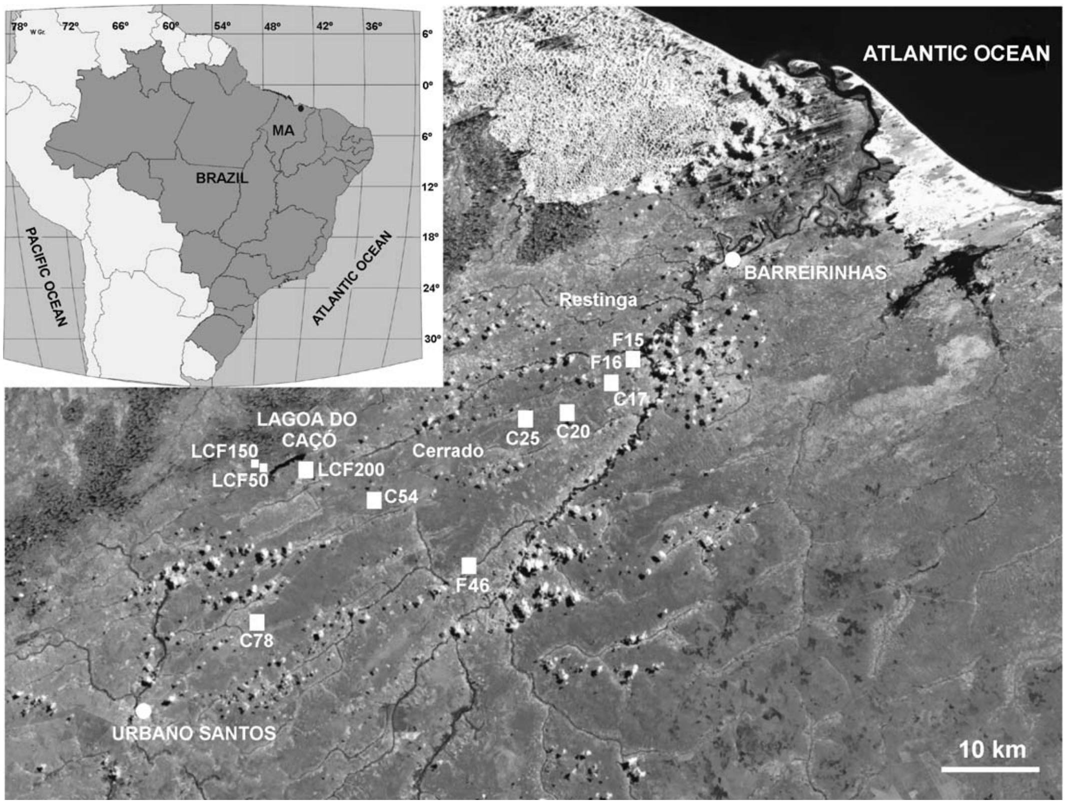

Figure 1. Map of Brazil showing the study site (MA—Maranhão State).

km 16 in an ecotone with Restinga vegetation and km 54, and is characterized by short trees (<10 m) such as *C. americana*, *Byrsonima verbascifolia*, *Annona coriacea* Mart., and C_4 grasses such as *Andropogon bicornis* L., *Aristida longifolia* Trin, *Panicum* sp., and *Paspalum* sp. (Ribeiro, 2002).

Sampling and methods

The soil of the study sites was classified as sandy soil (Typic Quartzipsament according to American soil taxonomy) over eolian sand. Soil samples were collected from eight points on a 78-km transect including Forest and Cerrado vegetation and in the forested sites LCF50, LCF150, and LCF200. Buried charcoal fragments were also collected from two sites (C25 and LCF200). Soil samples were collected from trenches or with a hand auger (Table 1).

From trenches, up to 5 kg of material were collected in 10-cm increments to a maximum depth of 300 cm. For $\delta^{13}C$ analysis, about 0.5 kg of soil and about 0.2 kg in the case of samples collected by a hand auger were sieved (5 mm) and dried at 50°C to a constant weight and root fragments were discarded by hand picking. The dry samples were sieved again (210 μm). For ^{14}C analysis, the buried charcoal fragments that were collected from soil samples at LCF200 received the conventional acid–alkaline–acid treatment (Pessenda et al., 1996b) and dried to a constant weight.

Table 1
Sites, vegetation types, sampling method, and geographic coordinates in the study transect

Code site	Vegetation and sampling method	Latitude (S)	Longitude (W)	Altitude (m)	Location
F15	Forest–Restinga transition—drilling	2°53′	42°54′	100	Barreirinhas
F16, C16	Restinga–woody savanna ecotone—drilling	2°53′	42°55′	100	Barreirinhas
C17	Woody savanna—drilling	2°54′	42°56′	100	Barreirinhas
C20	Woody savanna—drilling	2°54′	42°57′	100	Barreirinhas
C25	Woody savanna—trench	2°54′	42°60′	100	Barreirinhas
C54	Woody savanna—drilling	3°02′	43°13′	110	Urbano Santos
C78	Forest (cerradão)—drilling	3°11′	43°22′	110	Urbano Santos
F46	Forest—drilling	3°07′	43°05′	110	Urbano Santos
LCF50	Forest—drilling	2°58′	43°24′	110	Urbano Santos
LCF150	Forest—drilling	2°58′	43°26′	110	Urbano Santos
LCF200	Forest—trench	2°58′	43°20′	110	Urbano Santos

Grain size analyses were carried out at the Soil Science Department of the Escola Superior de Agricultura "Luiz de Queiroz," Piracicaba, Brazil, using the densimeter method (Kiehl, 1979) and the results are reported as clay percentage.

The carbon analyses on soils (total organic C, ^{13}C) were carried out at the Stable Isotope Laboratory of Centre for Nuclear Energy in Agriculture (CENA). Organic carbon results are expressed as percentage of dry weight. ^{13}C results are expressed as δ^{13}C with respect to PDB standard using the conventional δ (‰) notations:

$$\delta^{13}C(‰) = \left[\left(R_{\text{sample}}/R_{\text{standard}}\right) - 1\right]1000$$

where R_{sample} and R_{standard} are the ^{13}C/^{12}C ratio of the sample and standard, respectively. Analytical precision is ±0.2‰.

The ^{14}C analyses on charcoal fragments were carried out by Accelerator Mass Spectrometry (AMS) at the Isotrace Laboratory, University of Toronto, Canada. Radiocarbon ages are expressed as ^{14}C yr B.P. (before present) normalized to a δ^{13}C of −25‰ PDB and in cal yr B.P. (Stuiver et al., 1998).

Results

Soil properties and total organic carbon content

The grain size analyses show that the clay content is low (around 6–14%) in six locations (two around the Lagoa do Caçó and four in the 78-km transect), excepting km 46 (forest) that presents up to 28% of clay (Fig. 2).

Total organic carbon contents are shown in Figures 3 and 4. The carbon content data show a general decrease with depth. Values range from 4.44% in the shallow part of the soil to 0.04% in the deepest sample levels. The highest value was obtained at 50 m from the border of Lagoa do Caçó (LCF50) probably due to organic material deposition from the soil coluvium and/or this site represents an old lake shoreline (Fig. 4).

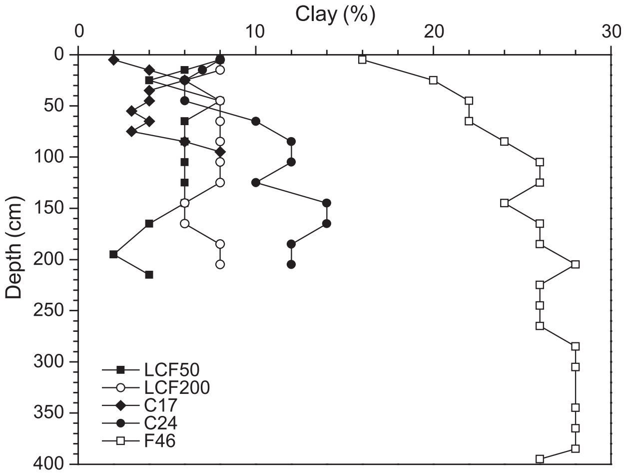

Figure 2. Clay fraction distribution with soil depth.

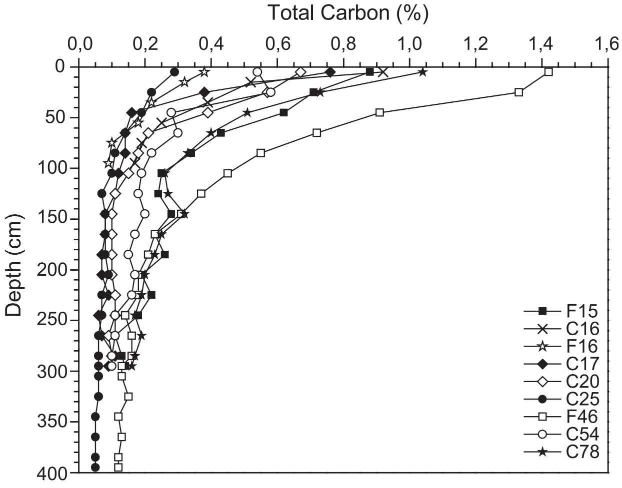

Figure 3. Total organic carbon variation with soil depth around the Lagoa do Caçó.

Chronology of charcoal fragments buried in the soil

The radiocarbon dates obtained in charcoal samples collected at site LCF200 showed an age profile that range from 1890 ^{14}C yr B.P. at depth of 30–40 cm, 2560 ^{14}C yr B.P. at 60–70 cm, 3870 ^{14}C yr B.P. at 80–90 cm, 4580 ^{14}C yr B.P. at 140–150 cm, and 8970 yr ^{14}C B.P. at 230–240 cm (Table 2, Fig. 5). Very similar charcoal chronology in relation to similar soil depths was obtained in distinct soils and locations in Brazil (Pessenda et al., 1996a, 1996b, 1998a, 1998b, 2001a, 2001b, 2004; Freitas et al., 2001; Gouveia et al., 2002). Calibrated ^{14}C ages in cal yr B.P. are also presented in Table 2; however, all results and discussions presented in the text are based on conventional ^{14}C yr B.P.

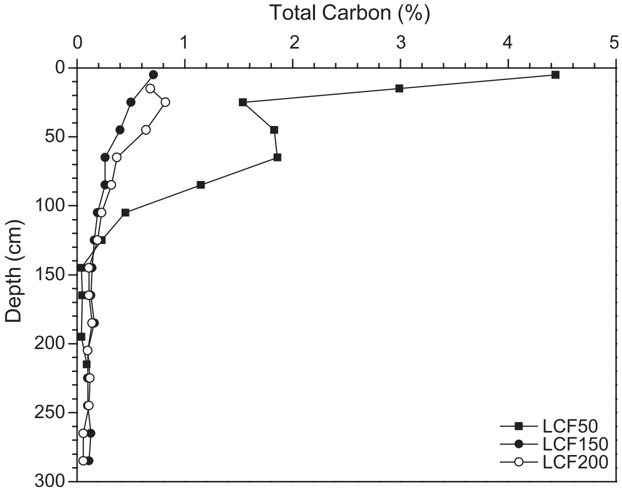

Figure 4. Total organic carbon variation with soil depth along the vegetation transect.

Table 2
Radiocarbon dates from charcoal fragments found in distinct soil depths at LCF200 site

Laboratory number	Depth (cm)	Ages (^{14}C yr B.P.)	δ^{13}C (‰)	Intercept ages (cal yr B.P.)
TO9145	30–40	1890 ± 60	−25.0	1875
TO9146	60–70	2560 ± 60	−22.9	2740
TO9147	80–90	3870 ± 60	−22.0	4340, 4280, 4270
TO9148	140–150	4580 ± 150	−21.0	5305
TO9149	230–240	8970 ± 70	−21.3	10,185

TO, Isotrace Laboratory, Toronto, Canada.

Charcoal distribution in the soil and chronology

Charcoal fragments distribution and the respective chronology for two profiles are presented in Figure 5. The results indicate the presence of significant amount of charcoal in most the profile reaching values as high as 0.4 g of charcoal fragments per kilogram of soil in the profile LCF200 around the Lagoa do Caçó. The ^{14}C data indicates increasing age with depth and an oldest age of 9000 ^{14}C yr B.P. was obtained at 230–240-cm soil layer. Charcoal fragments up to 0.1 g/kg of soil were also observed at site C25 that is presently covered by Cerrado vegetation.

δ^{13}C data on soil organic matter

The δ^{13}C data on SOM are presented in Figures 6 and 7. A wide range in δ^{13}C values that varies between −27.5‰ and −17.7‰ is observed in the surface soil samples collected in the 78-km transect. This pattern is a reflection of the dominant vegetation type present in each of the transect's sampling location. For example, the δ^{13}C value of −27.0‰ represents the forested vegetation at site F15 and the more enriched δ^{13}C value of −17.7‰ represents the open Cerrado vegetation (C54) (Fig. 6). The influence of vegetation type around the Lagoa do Caçó is also reflected in the δ^{13}C values that vary between −27.6‰ and −26.4‰ in the surface soil samples collected at this site (Fig. 7). This site is dominated by forest vegetation type. The transition areas are characterized by δ^{13}C values between −26.8‰ (F16) and −25.0‰ (C16) (Fig. 6).

The depth profiles data (Fig. 6) showed a wide range of isotopic trends. The denser forest site represented by F46 show a trend with depth from −27.5‰ to −24.9‰, which is typical of predominance of C_3 plants (forest vegetation). A similar pattern is observed at location F15. The sites representing the Cerrado vegetation dominated by C_4 plants showed much more enriched δ^{13}C values than the forest sites, ranging from −17.7‰ (0–10 cm) to −19.5‰ (290–300 cm) at site C54 and from −19.1‰ (0–10 cm) to −23.1‰ (390–400 cm) at site C25, where the most enriched value (−16.9‰) was obtained at 80–90-cm depth. Significant isotopic changes are also observed at the sites (C20, C17) closest to the transition Cerrado–Forest area. The isotope data (C20) showed an enrichment trend from −21.4‰ at the surface toward −18.7‰ at a depth of 70 cm. This trend reversed toward more depleted δ^{13}C values reaching −21.6‰ at a depth of 300 cm. At the site closest to the transition area (C17), the trend is from −24.2‰ at the surface toward −19.1‰ at 100-cm depth. This trend is reversed toward more depleted δ^{13}C values reaching a value

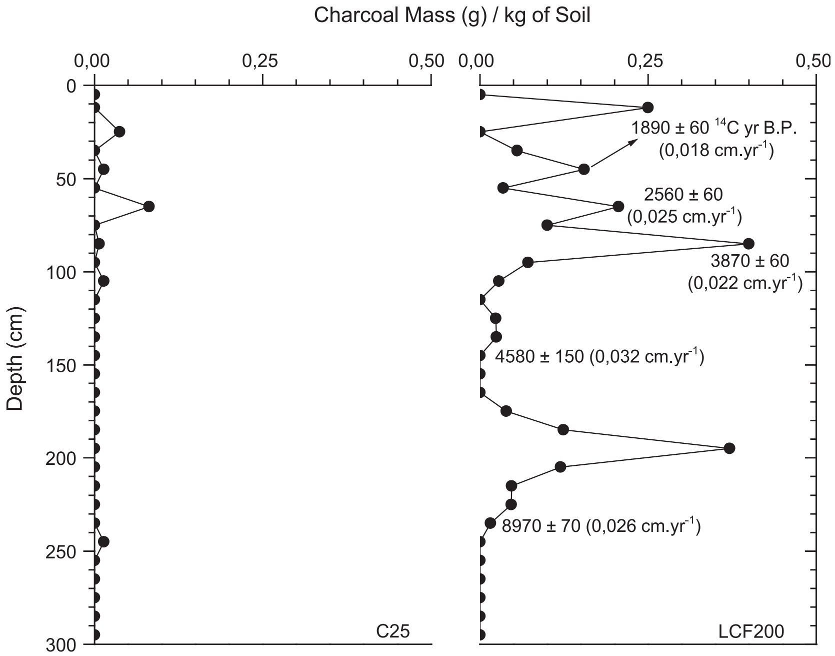

Figure 5. Charcoal concentration with soil depth in two sampling points and ^{14}C dating.

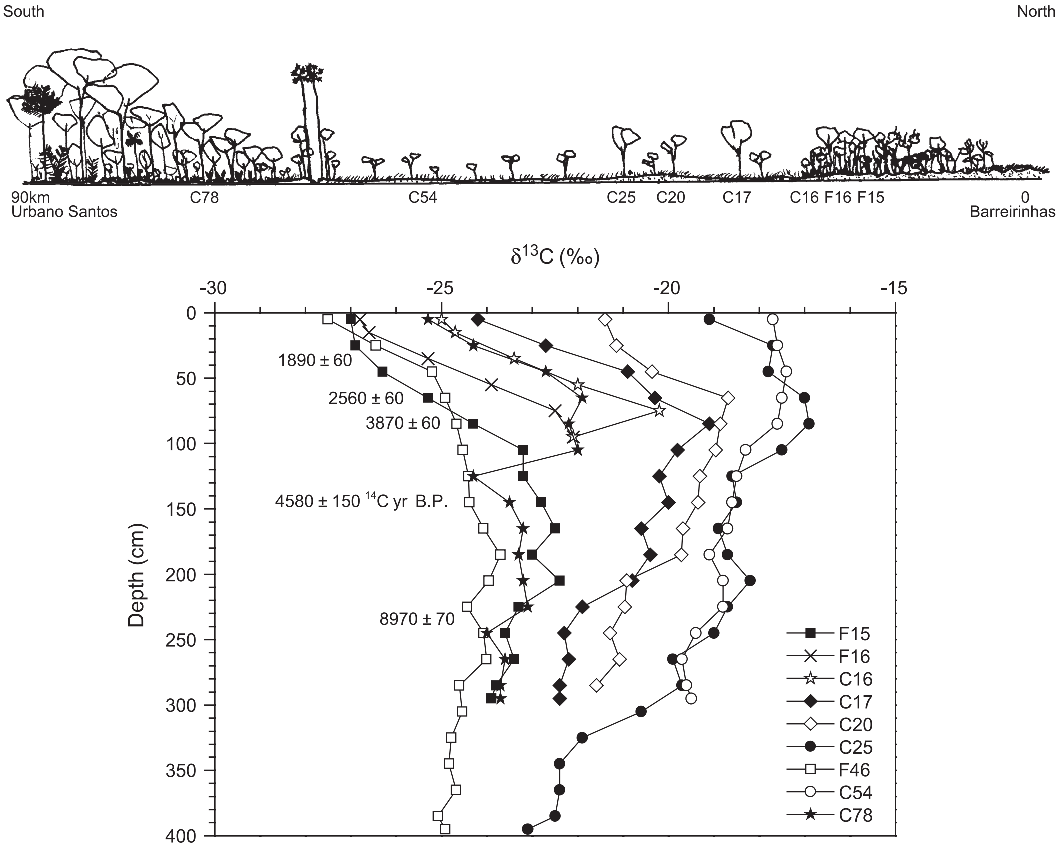

Figure 6. δ^{13}C variation and ^{14}C dating of charcoal samples from the ecosystem transect.

of −22.4‰ at a depth of 300 cm. The shallow core collected at the transition area (C16) showed slightly more depleted δ^{13}C values but a similar pattern than the profile collected at C17. The soil profiles collected at about 150–200 cm from the Lagoa do Caçó showed the same isotope pattern than the data collected at the transition areas (F16 and deepest part of C17). The site closer to the Lagoa do Caçó (LCF50) showed an isotope profile (Fig. 7) similar to the data observed at F15 that represent a forest site (Fig. 6).

The significant isotopic changes observed at the study site, which are represented by the profiles obtained at sites C25, C20, C17, LCF150, and LCF200, seems to start at the early Holocene (^{13}C enrichment trend) until ~4000–3000 ^{14}C yr B.P. Then, the trend reversed toward more depleted ^{13}C values starting from ~4000–3000 ^{14}C yr B.P. to the present time (Fig. 6).

Discussion

δ^{13}C variations in SOM and vegetation dynamics

The δ^{13}C patterns obtained in SOM profiles collected in the 78-km transect and the areas around the Lagoa do Caçó site have to be a reflection of vegetation changes that occurred at least during ~15,000 ^{14}C yr B.P. at the study site. This estimate is based on soil chronology data from other soil profiles in Brazil, with ca. 50 ^{14}C dates on charcoal fragments and humin fraction, which is the oldest and representative fraction of the SOM age (Balesdent, 1987), including late Pleistocene data in the range 17,000–12,000 ^{14}C yr B.P. (Pessenda et al., 1996a, 1996b, 1998b, 2001b, 2004; Freitas et al., 2001; Gouveia et al., 2002). The deeper soils could not be dated because no charcoal fragments were found at greater depths (>250 cm), and because of the very low carbon content of this sandy soil (Figs. 3 and 4), it was also not possible to obtain an efficient extraction of the humin fraction for ^{14}C dating. It is clear from the carbon isotope data that no major vegetation changes (i.e., arboreal community, C_3 plants to C_4 grasses) have occurred in the areas represented by site F46 (denser forest; δ^{13}C = −24.9‰ at the deepest layer to −27.5‰ at the soil surface) during the ~15,000 ^{14}C yr B.P. (Fig. 6). The isotope variation of 2.6‰ is probably related to the isotope fractionation that occurs during the SOM decomposition (Boutton, 1996; Nadelhoffer and Fry, 1988). Concerning modern areas vegetated with open savanna, a slightly enrichment (δ^{13}C = −19.5‰ to −17.7‰) have been observed in the areas around site C54 since the early Holocene (Fig. 6), probably indicating the presence of a woody/open savanna in this location in this period. The longest record for the savanna sites collected at site C25 indicated that during the late Pleistocene (~15,000 ^{14}C yr B.P.) and early Holocene, the site was probably vegetated

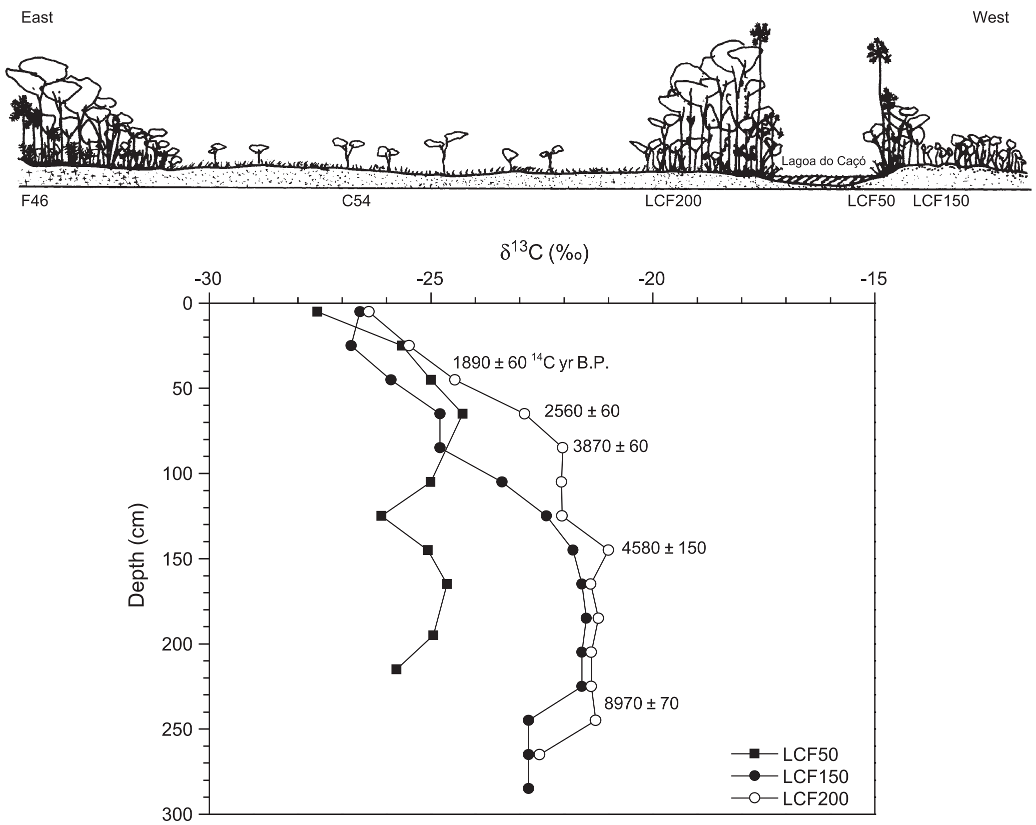

Figure 7. δ^{13}C variation with soil depth of sampling points around the Lagoa do Caçó.

with a woody savanna (δ^{13}C values of −23.1‰ to ca. −20.0‰) and the significant ^{13}C enrichment trend reaching values as high as −16.9‰ observed during the Holocene indicated a change toward a more open savanna vegetated by C_4 grasses. An isotope trend indicative of a change toward a more woody savanna seems to be observed in the last 4000–3000 ^{14}C yr B.P. (from 90- to 80-cm soil depth to surface) in this area. The vegetation changes inferred from the SOM at site C25 are also observed at the SOM isotope profiles obtained in the areas closer to the transition zone Cerrado–Forest (sites C20 and C17). In the area of C17 site, the isotope enrichment trend from −22.4‰ to −19.1‰ observed during early Holocene until 4000–3000 ^{14}C yr B.P. is an indication of an opening of woody savanna vegetation (probably associated with the expansion of C_4 plants) and a trend toward −24.2‰ observed in the late Holocene indicated the presence of more C_3 plants (wooden savanna). A similar pattern is observed at site C20 with a change toward more open savanna vegetation (−21.4‰) in the last ~3000 ^{14}C yr B.P.

Based on carbon isotope values, it is possible to hypothesize that the expansion of C_4 plants (opening of vegetation) in the ecosystem transect seems to start since the early Holocene (around 9000 ^{14}C yr B.P.), probably from the site C54 (more open vegetation since the late Pleistocene/early Holocene period) to sites C25, which presented the most enriched value at 90–80-cm soil depth (4000–3000 ^{14}C yr B.P.), C20 and C17. The C_4 plants' expansion did not significantly affect the area around site F15 during the early and mid-Holocene period (values around −23.9‰ to −22.8‰), and a trend from ca. 90- to 80-cm soil depth toward more depleted values (−27.0‰) in the soil surface indicates the expansion of the arboreal community in the last 4000–3000 ^{14}C yr B.P.

The presence of wooden savanna vegetation in some areas of the study site during the Holocene can also be documented from a comparison between the charcoal content data and the δ^{13}C profiles obtained at sites C25 and LCF200. The δ^{13}C data from site C25 indicated that from the late Pleistocene to the present, this area has been mainly dominated by C_4 plants (Fig. 6). This is also reflected in the low charcoal content obtained at this site (Fig. 5). In ecosystems with the predominance of thin fuel (grasses), most of the biomass is burned during the flame emission periods (high efficiency of the combustion) and the productivity of charcoal is not significant, consisting mainly of small particles (<1 mm) (Stocks and Kauffman, 1997). The δ^{13}C values of −22.5‰ to −21‰ observed during the period 9000–4000 ^{14}C yr B.P. at site LCF200 (Fig. 7) indicated the area was vegetated by a woody savanna. Considering an isotope fractionation due to the SOM decomposition (Boutton, 1996) of ca. 3‰ in Brazilian soils (Gouveia et al., 2002; Pessenda et al., 1998a, 1998b, 2001a), it is hypothesized that a moderate (not drastic) increase in the arboreal vegetation ($\delta^{13}C = -22.0‰$ to $-26.4‰$) occurred during late Holocene This is supported by the high charcoal content obtained in SOM at this site during the Holocene (Fig. 5), probably related to the higher number of trees (fuel) available in comparison to savanna areas. According to Stocks and Kauffman (1997), in forests greater quantities of biomass are consumed during the incandescent phase, where the combustion is less efficient, resulting in the production of greater amount of charcoal.

Paleoenvironmental reconstruction

Based on the data obtained at the study site, it is possible to postulate that approximately since the late Pleistocene (~15,000 ^{14}C yr B.P) to the early Holocene (~10,000–9000 ^{14}C yr B.P), arboreal vegetation comprising of forest and woody savanna covered most of the ecosystem transect of 78-km constituted actually of Forest–Cerrado–Restinga ecotone on the Barreirinhas region. This phase was probably related to a more humid phase. Afterward, since ~9000 ^{14}C yr B.P. till 4000–3000 ^{14}C yr B.P., the Cerrado expanded, probably related to the presence of a drier climate. The high concentration of charcoal found at the study site (Fig. 5) confirms the occurrence of a drier phase during this period. From approximately 4000–3000 ^{14}C yr B.P. to the present, a trend toward more depleted $\delta^{13}C$ of SOM in several points of the study transect was interpreted as a forest expansion over the Cerrado due to the return to a more humid phase and probably similar to the present climate. The interpretation based on ^{13}C data in SOM agrees with paleovegetation and paleoclimate reconstruction inferred from pollen analysis in lake sediments collected in the Lagoa do Caçó that occupies a small closed basin (~15 km^2) in Maranhão State (2°58′ S/43°25′ W; 120-m elevation) (Ledru et al., 2001). This lake is located about 10 km southwest of the ecosystem transect sampled for the ^{13}C study in SOM. Three SOM profiles were also collected around the Lagoa do Caçó (Fig. 7), which allow us a direct comparison with the lake sediment record. The charcoal chronology was obtained in one of these soil profiles (LCF200). The lake sediment record spans at least the past 18,000 ^{14}C yr B.P. Around 14,000 ^{14}C yr B.P., based on the presence of *Didymopanax*, Myrtaceae, Moraceae, and *Podocarpus*, there was an expansion of the forest. This plant community and the high percentages of tree pollen (80%) are typical of modern pollen spectra from gallery forest in the Brazilian Cerrado (woody savanna) vegetation and are connected with moist and cold winter conditions (Ledru et al., 2001). The ^{13}C record obtained at sites representative of the present forest and open savanna vegetation showed the presence of forest vegetation during the late Pleistocene. The arrival of *Picramnia* and Mimosaceae and the decline of *Podocarpus* ca. 12,000 ^{14}C yr B.P. suggest an increase in temperature. The presence of *Cecropia*, a pioneer species associated with the drastic destruction of moist tropical forests between 11,000 and 10,000 ^{14}C yr B.P., indicated a change toward savanna-type vegetation. The presence of charcoal and a high percentage of grass pollen (60%) support this interpretation. The dominance of Poacea (50%) and *Picramnia* (10%) pollen after 10,000 ^{14}C yr B.P. suggested the decrease of the gallery forest around the lake and the dominance of open savanna communities (Ledru et al., 2001). The ^{13}C record obtained in SOM around the lake (Fig. 7) showed the presence of woody savanna (values around $-23‰$ to $-21‰$) since ~10,000–9000 ^{14}C yr B.P. to ~4000–3000 ^{14}C yr B.P., which is supported by pollen analysis that indicated the woody savanna vegetation after 7500 ^{14}C yr B.P., based on the expansion of tree species (*Byrsonima*, *Curatella,* Mimosaceae), which taxa are considered as good species indicator for Cerrado (woody savanna) today and indicative of a seasonal climate (Ledru et al., 2002). After ~4000–3000 ^{14}C yr B.P. (Fig. 7), the $\delta^{13}C$ values showed a moderate and perhaps progressive (not abrupt) increase of the arboreal density (not observed in the pollen record of central core of Lagoa do Caçó) that gave origin to the present forested vegetation around the lake, indicating a change toward more humid condition. Sedimentological studies (seismic profiles, mineralogy, and organic geochemistry) developed in two cores from the center and margin of Lagoa do Caçó indicated that the Holocene climatic variability was not detected in the central core (MA 97-1) used for pollen analysis. In contrast, the record obtained from the lake margin (core MA 97-3) showed a decrease in sedimentation rates and a hiatus in the interval 12,500 ^{14}C yr B.P. to 5600 ^{14}C yr B.P. The interpretation of these data suggested that the Holocene was characterized by lower moisture availability and a distinct dry period until 7000 yr B.P. (Sifeddine et al., 2003), which corresponds to ca. 6000 ^{14}C yr B.P. Environmental conditions approached those prevailing today around 5610 cal yr B.P. (Jacob et al., 2004b), which correspond to ca. 4900 ^{14}C yr B.P. These data are in good agreement and reinforce the carbon isotope data interpretation for the Holocene period. The presence of high concentration of charcoal in soils (Fig. 5) is probably an indication of drier conditions mainly during the early to mid-Holocene, since during the late Holocene, the anthropogenic events cannot be discarded. However, no evidences of human influences (bones, ceramic fragments, rock paintings, fruit seeds) were found in the 11 sampling locations and other sites in the study area. A pollen record obtained by De Oliveira et al. (1999) in the north region of Bahia (NE Brazil) and distant ca. 1200–1300 km south of Barreirinhas region indicated a wet early Holocene following with the progressive installation of dry period in the middle Holocene. These differences can probably be explained through air masses forcing and sea–atmosphere interactions (Ledru et al., 2002).

The paleovegetation patterns, inferred from carbon isotopes in SOM (this study) and pollen analysis in lake sediments in northeastern Brazil, have also been documented in other regions of Brazil. Several studies based on carbon isotopes in SOM have found evidences for the early–

middle Holocene dry phase in southern Brazil (Pessenda et al., 1996a), southeastern Brazil (Gouveia et al., 2002; Pessenda et al., 1996a), and parts of the Amazon basin (Desjardins et al., 1996; Pessenda et al., 1998a, 1998b, 2001a; Freitas et al., 2001). Pollen analyses in lacustrine sediments in southern (Behling, 1995), southeastern (Behling et al., 1998), and central (Barberi et al., 2000) Brazil also documented the early–mid-Holocene dry period. In the central Amazon, evidences of the middle Holocene dry phase were also found (Sifeddine et al., 2001). The presence of forest during the late Pleistocene early Holocene has been documented in the central (Colinvaux et al., 1996; Haberle and Maslin, 1999; Sifeddine et al., 2001) and southern (Freitas et al., 2001; Pessenda et al., 1998b, 2001a) parts of the Amazon basin. All these studies, similarly to the data obtained in northeastern Brazil, showed an expansion of the forest vegetation indicative of a more humid phase during the last ~3000 ^{14}C yr B.P.

It seems that the dry phase started earlier in the southeastern and southern regions of Brazil. Carbon isotope data obtained in Salitre, Minas Gerais State (Pessenda et al., 1996b), Piracicaba, São Paulo State and Londrina, Paraná State (Pessenda et al., 1996a), and Jaguariúna, São Paulo State (Gouveia et al., 2002) showed a significant presence of C_4 grasses since ~11,000 to ~4000 ^{14}C yr B.P. Pollen data from lake sediments also indicated a dry climate in similar period in sites in southern and southeast Brazil (Behling, 1995; Behling et al., 1998; Ledru et al., 1996).

In southern Brazil between about 11,000 ^{14}C yr B.P. until 9000–8000 ^{14}C yr B.P., the C_4 grasses and a dry climate were predominant in several locations; in the northeastern region and in the southern Amazon region, forest vegetation was dominant, which is probably associated to a humid climate. From ca. 8000–7000 ^{14}C yr B.P., a dry climate was also observed in the northeastern, southern, and central regions of Amazon region, modifying from ca. 4000 to 3000 ^{14}C yr B.P. for a more humid climate in association with other sites in southern and southeastern regions as described earlier.

It has been speculated by Martin et al. (1997) that these climate changes could be related to the position of Inter-Tropical Convergence Zone (ITCZ) between 12,400 and 8800 cal yr B.P., which correspond to ca. 10,500 ^{14}C yr B.P. and 7300 ^{14}C yr B.P. Also, according to these authors, the present precipitation over the South America continent is amply controlled by seasonal movements of ITCZ. During the summer, the ITCZ moves to the south due to the heating of continent. In the period 12,400 and 8800 cal yr B.P., the eastern part of the Amazon received substantial moisture, while the Bolivian Altiplano (located more in the south and to the east) was arid. They suggested that the fact was related to the ITCZ position more in the north during the summer, in relation to the present days. In similar form, in the mentioned period, the northeastern and Amazon regions presented higher precipitations than the southern region, resulting to more humid climate in the north and drier climate in the south, between approximately 10,500 and 7300 ^{14}C yr B.P.

Conclusions

Significant carbon isotope variations reflecting changes in vegetation were observed in a 78-km transect across the forest (coastal vegetation and semideciduous forest) and woody savanna ecosystems. Three major vegetation phases were identified. These include (i) a forest phase between ~15,000 and ~9000 ^{14}C yr B.P., (ii) cerrado (woody savanna) expansion between ~9000 and 4000–3000 ^{14}C yr B.P., and (iii) forest expansion after ~3000 ^{14}C yr B.P. The presence of palaeofires reinforce the dry early–mid-Holocene period. Our results agree with results of lake and marine sediments of NE Brazil for the wet late Pleistocene–dry early Holocene period and with a peat bog pollen study in the Bahia State and lake sediment results in Maranhão State for the dry mid-Holocene. In addition, our results agree with results of carbon isotope analysis of SOM and pollen studies developed, respectively, in the south and central Amazon region, where the forest was predominant during the late glacial and savanna expansion was observed during the dry and warm early and middle Holocene. After ~3000 ^{14}C yr B.P., a similar forest expansion related to a moister period was characterized, implying that similar climatic conditions have affected these areas during the late Pleistocene until the present.

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