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Holocene palaeoenvironmental reconstruction in northeastern Brazil inferred from pollen, charcoal and carbon isotope records

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Abstract: Soils in the Barreirinhas region, Maranhão State, were sampled for $\delta^{13}C$ analysis and buried charcoal fragments in the soils were radiocarbon dated. Three soil profiles collected in forested areas around the Lagoa do Caçó and one in a woody savanna (mixture of non-arboreal and arboreal species) located approximately 10 km southeast of the Lagoa were studied. A high-resolution pollen record was obtained from lake sediments, showing that forest vegetation was predominant in the area in the early Holocene. From approximately 10 000 ^{14}C yr BP the pollen spectrum gradually changed, suggesting the dominance of open savanna communities, these were transformed to a more forested landscape (woody savanna) from approximately 7500 yr BP. The lake sediments also record evidence of fire (indicated by buried charcoal particles at several soil depths) during the Holocene. The $\delta^{13}C$ analysis of soil organic matter (SOM) indicates that from between approximately 10 000 yr BP and 9000 yr BP to ~4000 yr BP, a woody savanna prevailed at two sites around the lake, probably reflecting a drier climate. From ~4000–3000 yr BP to the present, the results indicate a moderate and progressive increase in arboreal vegetation around the lake as a result of the return to more humid climate conditions probably similar to the present-day. The carbon isotope results from the site located 10 km from the lake indicate the presence of an open vegetation from the early Holocene. In general, there is agreement between the palaeovegetation patterns inferred from the pollen and carbon isotope data. However, a much less uniform landscape, with a mosaic of different ecosystems at any given time, is inferred from the carbon isotope record.

Key words: Pollen, lacustrine sediment, soil, carbon isotopes, charcoal, palaeovegetation, Holocene, northeastern Brazil.

Introduction

During the Holocene the retreat of glacial ice sheets at both poles induced a weaker climatic gradient between poles and equator than during glacial episodes (Ledru *et al*., 2002; Overpeck *et al*., 2003). By contrast, the biosphere, which shows maximum expansion during interglacials, had a much greater influence on climate. Therefore, to document Holocene climatic variations we need to investigate past vegetation changes in the tropics, where the richest biomes occur at the present-day.

Palaeoenvironmental reconstructions in the tropics have been carried out using a multidisciplinary approach. The results have provided new insights into regional palaeoclimatic settings. This approach has proved to be effective in various

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areas of Brazil (Absy *et al.*, 1991; Ledru *et al.*, 1996; Behling *et al.*, 2000; Sifeddine *et al.*, 2001) and, in some instances, has led to the validation of new paleoenvironmental proxies (Bertaux *et al.*, 1996; Jacob *et al.*, 2004). However, rarely have results inferred from pollen and carbon isotopes from soil organic matter (SOM) records been compared in the same area for the same time interval.

Pollen records obtained from lacustrine sediments have been used for palaeoenvironmental reconstruction studies during the late Quaternary and the Holocene in several regions of Brazil (Absy and van der Hammen, 1976; Roth and Lorscheitter, 1993; van der Hammen and Absy, 1994; Behling, 1995a,b, 1997a,b; Colinvaux *et al.*, 1996; Ledru *et al.*, 1996; Salgado-Laboriau *et al.*, 1997). In addition, the SOM carbon isotope technique has also been applied to reconstruct palaeoenvironmental changes in the southern (Pessenda *et al.*, 1996a), southeastern (Pessenda *et al.*, 1996a, 2004a; Gouveia *et al.*, 1999a, 2002), central (Pessenda *et al.*, 1996b) and northern regions of Brazil (Desjardins *et al.*, 1996; Gouveia *et al.*, 1997; Freitas *et al.*, 2001).

The stable carbon isotope composition ($\delta^{13}C$) of SOM contains information regarding the presence/absence of C_3 and C_4 plant species in past plant communities, and their relative contribution to community net primary production (Throughton *et al.*, 1974). The $\delta^{13}C$ values of C_3 plant species (trees) range from approximately $-32‰$ to $-20‰$ Pee-Dee Belemnite (PDB), with a mean of $-27‰$, while, in contrast, the $\delta^{13}C$ values of C_4 species (grasses) range from $-17‰$ to $-9‰$, with a mean of $-13‰$. Thus, C_3 and C_4 plant species have distinct $\delta^{13}C$ values and differ from each other by approximately 14‰ (Boutton, 1996).

Studies of palaeoenvironmental changes are rare in northeastern Brazil, probably because of the scarcity of stable and perennial lakes and the aridity of the climate. However, the few studies carried out in this region have shown that important changes in vegetation and climate occurred in this area, with significant differences according to latitude. One study carried out in a peat bog in the Icatu River valley in the semi-arid region of Bahia State, documented vegetation and climate changes during the last 11 000 yr BP (De Oliveira *et al.*, 1999), with a humid and cold period during the early Holocene, becoming progressively drier during the Holocene. In the northernmost region, the vegetation was scarce and open at the beginning of the Holocene, changing progressively toward a woody savanna (Behling *et al.*, 2000; Ledru *et al.*, 2002). At Lagoa do Caçó, Maranhão State, a molecular fossil detected in the sediment attests to a strong aridity at the beginning of the Holocene (Jacob *et al.*, 2004) and a distinct dry period until 7000 cal. BP (*c.* 6000 yr BP), despite the gradual increase in lake water level inferred from sedimentological and geochemical analysis (Sifeddine *et al.*, 2003). These environmental changes were, respectively, related to the influence of the North Atlantic climate reversal or Younger Dryas recorded as far south as these tropical latitudes (Hughen *et al.*, 1996; Ledru *et al.*, 2002), followed by a strong precession signal that had a major impact on seasonality in the tropics (Martin *et al.*, 1997; Ledru *et al.*, 1998).

In this paper, we present a regional analysis of the environmental changes that affected the northeastern region of Brazil, involving, for the first time, direct comparisons between lacustrine sediment deposits and soil carbon isotope records. We aim to validate the ability of the carbon isotopes to reconstruct regional palaeoenvironmental changes and to show how the use of this indicator can provide valuable information complementary to that obtained from pollen analysis.

Study area

The study site is located in northeastern Brazil (2°52′ S/45°55′ W and 3°11′ S/43°22′ W, 100–120 m a.s.l) (Figure 1). A mean annual temperature of around 26°C and a mean annual precipitation of 1500–1750 mm/yr (six-month rainy season from December to May) characterize the tropical semi-humid climate of the region (Nimer, 1989). Seasonality is controlled by the latitudinal shifts of the Inter Tropical Convergence Zone (ITCZ). Lagoa do Caçó (2°58′ S/43°25′ W) occupies a small closed basin area (15 km^2). The modern-day vegetation consists of aquatic species in the lake and various ecosystems in the surrounding areas as follows: gallery forest, cerrado (woody savanna), Restinga (coastal vegetation) and mangrove. The lake margins are occupied by herbaceous plants of Cyperaceae (*Eleocharis* sp.), Orchidaceae and Eriocaulaceae, *Mauritia flexuosa* (a palm that forms large mixed colonies in seasonally flooded marshland with *Xylopia*), and trees from the gallery forest (Melastomataceae, *Tapirira guianensis* (Anacardiaceae), *Vochysia tucanorum* (Vochysiaceae), *Cordia nodosa* (Boraginaceae), *Casearia* spp. (Flacourtiaceae), *Ficus* spp. (Moraceae) and *Picramnia* spp. (Simaroubaceae). The Cerrado profiles vary according to the density of the trees, including *Stryphnodendron adstringens* (Mimosaceae), *Parkia pendula* (Mimosaceae), *Qualea grandiflora* (Vochysiaceae) and *Curatella americana* (Dilleniaceae). The coastal vegetation (Restinga) was encountered on the dunes and included small trees and shrubs (e.g., *Byrsonima* spp. (Malpighiaceae), *Copaifera* spp. (Caesalpiniaceae), *Hymenaea* sp. (Fabaceae), *Caryocar coriaceum* (Caryocaraceae)) and many Bromeliaceae; the dominant herbaceous plant being *Chamaecrysta flexuosa* (Fabaceae) (Ribeiro, 2002; Ledru *et al.*, 2002).

Methods

A 345-cm sediment core was collected with a Vibracorer in 1997 (Martin *et al.*, 1995) from an area close to the centre of the lake where the water depth is about 12 m. Sediment samples (8 cm^3) were processed by standard methods (Faegri and Iversen, 1989) for pollen analysis and detailed pollen diagrams are published in Ledru *et al.* (2002, 2005). Between 300 and 400 pollen grains have been counted per sample. The charcoal data (g/cm^2) have been obtained using the method developed by Clark (1982). A chronologic framework for the sedimentary sequence was provided by 14 conventional and accelerator mass spectrometer (AMS) radiocarbon dates (Table 1) (Ledru *et al.*, 2002).

Soil samples were collected at three forested points located 50, 150 and 200 m (at this last point, buried charcoal fragments

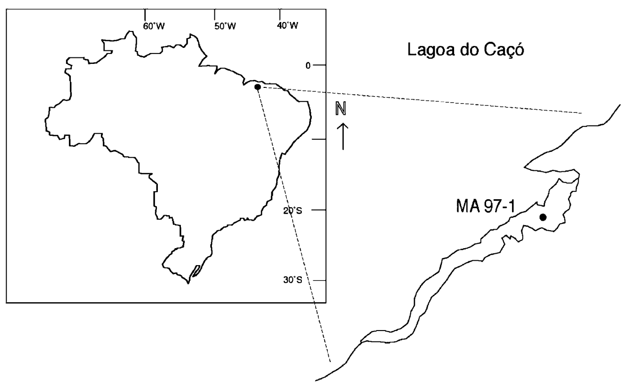

Figure 1 Map of Brazil showing the study site

Table 1 Radiocarbon ages of total organic matter from Core MA97-1

Laboratory number[a]	Depth (cm)	Age (^{14}C yr BP)
Beta110192	18–23	3060 ± 50
AA32146	31–32	3830 ± 60
Beta115180	40–45	5090 ± 60
AA32147	48–49	5580 ± 80
Beta110193	95–100	7660 ± 50
AA32148	118–120	9040 ± 90
Beta110194	135–140	9720 ± 50
Beta110195	172–174	10 880 ± 50
AA32149	178–180	11 605 ± 120
AA32150	200–202	12 640 ± 135
Beta115181	215–218	12 930 ± 90
AA32151	241–242	13 560 ± 1185
AA32153	259–260	15 400 ± 180
Beta110196	275–277	15 870 ± 60

[a]Beta, Beta Analytic, Miami, USA; AA, University of Arizona, Tucson, USA.

were also collected from the soil profile) from the border of Lagoa do Caçó (Table 2; Figure 2). These points were identified as LCF50 located near the margin of the lake in an area covered today with gallery forest, LCF150 located in a dry forest environment and LCF200 in the cerradão (dense woody savanna) vegetation. Sampling point C25, a Cerrado (woody savanna) site, is located at 25 km (2°54′ S/43°60′ W) along a 78-km-long forest–savanna ecosystem transect and approximately 10 km distant from Lagoa do Caçó.

The sandy soil (Typic Quartzipsament in the American Soil Taxonomy – USDA classification) was developed on aeolian sand. Soil samples were collected from a trench or with a hand-auger (Table 1).

Up to 5 kg of material was collected from trenches in 10-cm increments to a maximum depth of 300 cm. For δ^{13}C analysis, about 0.2 kg of soil was sieved (5 mm), dried at 50°C to a constant weight and root fragments were discarded by hand-picking. The dry samples were sieved again (210 μm) and any remaining debris was removed by flotation in 0.01 M hydrochloric acid and wet sieved. For ^{14}C analysis, the buried charcoal fragments that were collected by hand-picking from soil samples at LCF200, received the conventional acid–alkaline–acid treatment (Pessenda *et al*., 1996b) and were dried to a constant weight.

The carbon analyses on soils and plants (total C, δ^{13}C) were carried out at the Stable Isotope Laboratory of CENA. Results are expressed, respectively, in percentage of dry weight and as δ^{13}C with respect to PDB standard using the conventional δ (‰) notations

$$\delta^{13}\mathrm{C}\ (‰) = [(R_{\mathrm{sample}}/R_{\mathrm{standard}}) - 1]\cdot 1000 \qquad (1)$$

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

The ^{14}C analyses of charcoal fragments were carried out by AMS at Isotrace Laboratory, University of Toronto, Canada. Radiocarbon ages are expressed as ^{14}C yr BP (before present), normalized to a δ^{13}C of −25‰ PDB.

Results and discussion

Pollen and carbon isotope records

Although the sediment record spans at least the past 18 000 years (Figure 3a, 4), results and discussion will be centred on the last 10 000 yr BP in order to better compare our analyses and interpretations.

The pollen record (Figure 4) shows that the forest expansion that occurred during the end of the Pleistocene, between 14 000 yr BP and approximately 11 000 yr BP, ended abruptly at *c*. 10 000 yr BP. Dense gallery forest plant communities were replaced by *Cecropia*, a pioneer species associated with the drastic reduction of tropical forests. The pollen record attests to high frequencies of grass pollen (60%) dominated by Poaceae (50%). After 10 000 yr BP, the pollen spectra showed a progressive change toward a slow restructuring of the gallery forest around the lake and the dominance of a woody savanna. At *c*. 7500 yr BP the landscape became more forested as other tree taxa started to grow (*Byrsonima*, *Curatella*, Mimosaceae). These taxa are considered good indicator species for Cerrado (woody savanna) vegetation today. The high content of charcoal found after 7500 yr BP (Figure 3c) in the lake sediments also points to the occurrence of a woody savanna during this period.

The expansion of a woody savanna vegetation in this region during the Holocene, inferred from the pollen record, is also documented from a comparison between the charcoal content (Figure 3d, 3e) and the δ^{13}C profiles obtained in soils at sites LCF50, LCF150, LCF200 and C25 (Figure 3f and Table 3). The radiocarbon data showed that the record obtained in the soil profile at LCF200 site in the depth interval 0–240 cm represents the last 9000 yr BP (Figure 3 and Table 4). However, based on soil chronology data obtained at similar soil profile depths in Brazil that covered the range 17 000 yr BP to the Holocene period (Pessenda *et al*., 1996b, 1998a,b, 2001a, 2004a,b; Gouveia *et al*., 1999a,b, 2002; Freitas *et al*., 2001), the deepest SOM profile (330 cm) analysed in the study should represent at least the last 12 000–13 000 yr BP.

In our interpretation of the SOM δ^{13}C profiles, we assume that variations smaller than 4‰ are associated with isotopic discrimination (fractionation) that occurs during organic matter decomposition and with variations in the carbon isotope composition of atmospheric CO_2 (Nadelhoffer and Fry, 1988; Boutton, 1996). We infer that higher variations than 4‰ have resulted from changes in the plant community (Cerri, *et al*., 1985; Boutton, 1996; Desjardins *et al*., 1996). We also assume that soil accumulation was not significantly affected by bioturbation and/or translocation, since the ^{14}C ages (chronology) of buried charcoal fragments were in good relationship (no age inversion) with soil depth. To reinforce our assumption, a similar isotopic trend was also observed (early to mid-Holocene ^{13}C enrichment and late Holocene ^{13}C depletion) at 11 points located in the same region (Pessenda *et al*., 2004b).

Table 2 Sites, vegetation types, sampling method and geographic coordinates

Code Site	Vegetation and sampling method	Lat. (S)	Long. (W)	Alt. (m)	Location
LCF50	Forest – drilling	2°58′	43°24′	110	Barreirinhas
LCF150	Forest – drilling	2°58′	43°26′	110	Barreirinhas
LCF200	Forest – trench	2°58′	43°20′	110	Barreirinhas
C25	Woody Savanna – drilling	2°54′	42°60′	100	Barreirinhas

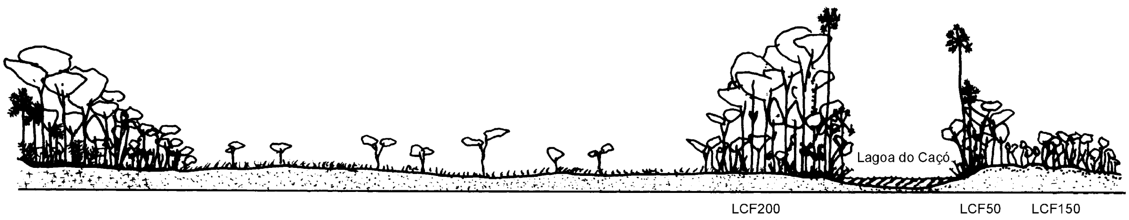

Figure 2 Ecosystem profile showing the sampling points around the Lagoa do Caçó

A significant difference is observed in the carbon isotope profiles obtained at the location close to the lake in comparison with the other sites located at 150 and 200 m from the lake shore, and the site located 10 km from the Lagoa do Caçó (Figure 3f anf Table 3). The carbon isotope data with $\delta^{13}C$ values around $-25‰$ indicated that, during most of the Holocene, the area around site LCF50 was covered by a dense woody savanna, which is in agreement with the information inferred from the pollen analysis. A more recent $\delta^{13}C$ change toward $-27‰$ in the shallow part of the soil suggests a change toward a forest-dominated ecosystem. The carbon isotope data obtained at LCF150 and LCF200 ($\delta^{13}C$ values $-21‰$ to $-23‰$) indicate that, for most of the Holocene, the area represented by these sites was covered by a woody savanna. As with the site close to the lake, a $\delta^{13}C$ change toward $-26.6‰$ points to the presence of a forested ecosystem in the late Holocene, indicating a change toward more humid conditions than in the middle Holocene. The changes seem to start earlier ($\sim$4000 yr BP) in the area located around 150 m from the lake shore than in the area around 200 m ($\sim$3000 yr BP). The changes toward the present vegetation in the late Holocene inferred from the soil profiles are not recorded in the pollen diagram. The high content of charcoal fragments found at site LCF200 supports the existence of a dense woody savanna during most of the Holocene in the area represented by this site. Probably it is an indicaton of drier conditions during the early to mid-Holocene, however anthropogenic effects cannot be ruled out for the late Holocene. Evidence of human occupation (bones, ceramics, fruit seeds, rock paints) was not found in the study region. The area represented by site C25, which produced $\delta^{13}C$ values ranging between $-16.9‰$ and $-19.1‰$, and the lower content of charcoal fragments found at this site compared with site LCF200 indicates that for the whole of the Holocene, this area was dominated by an open savanna with some trees. In agreement with the pollen record, this longest record (Figure 3f) indicates that during the late Pleistocene the area was dominated by forested vegetation. The $\delta^{13}C$ values in the deeper part of the profile, which should represent this time, range between $-22‰$ and $-20‰$ (Figure 3f). Today, this area is covered by open savanna with some trees.

Overall, there is agreement between the information obtained from the pollen and the carbon isotope records. However, it seems the pollen diagram does not record the change from woody savanna to forest in the late Holocene, as indicated in the carbon isotope data for the area around 200 m from the lake. The existence of an open savanna with some trees, inferred from the isotope data at the site located 10 km from the lake, is not fully registered in the pollen record. The small differences in timing or composition of the vegetation

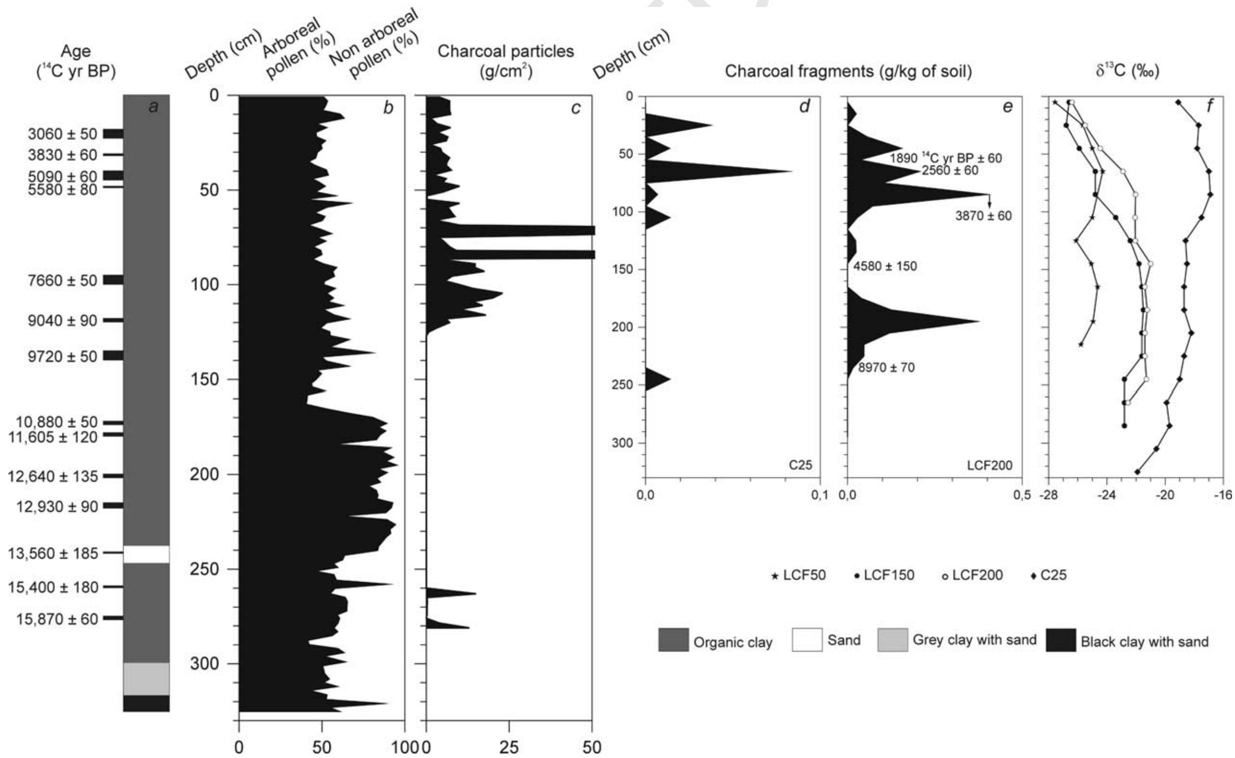

Figure 3 (a) Lake sediment record and radiocarbon dating of organic material, (b) pollen diagram, (c) charcoal distribution in the sediment, (d) charcoal distribution in the soil at site C25, (e) charcoal distribution in the soil at site LCF200 and radiocarbon dating, (f) $\delta^{13}C$ results of SOM with depth at sites LCF50, LCF150, LCF200 and C25

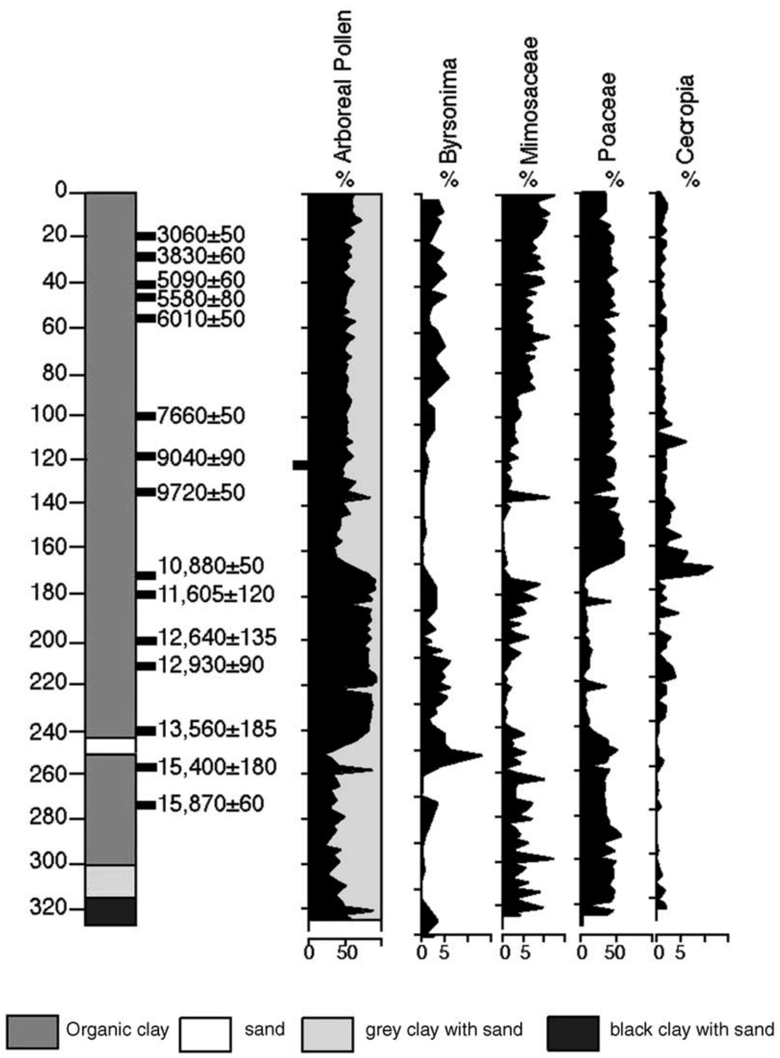

Figure 4 Summary pollen percentage diagram for MA97-1 (Lagoa do Caçó) showing taxa discussed in the text

Table 3 Soil depth $\delta^{13}C$ (‰) values of sampling locations

Soil depth (cm)	$\delta^{13}C$ (‰)			
	LCF50	LCF150	LCF200	C25
00–10	–27.6	–26.6	–26.4	–19.1
20–30	–25.6	–26.8	–25.5	–17.7
40–50	–25.0	–25.9	–24.5	–17.8
60–70	–24.3	–24.8	–22.9	–17.0
80–90	NA	–24.8	–22.0	–16.9
100–110	–25.0	–23.4	–22.1	–17.5
120–130	–26.1	–22.4	–22.0	–18.6
140–150	–25.1	–21.8	–21.0	–18.5
160–170	–24.6	–21.6	–21.4	–18.9
180–190	NA	–21.5	–21.2	–18.7
190–200	–24,9	NA	NA	NA
200–210	NC	–21.6	–21.4	–18.2
210–220	–25.8	NA	NA	NA
220–230	NC	–21.6	–21.4	–18.7
240–250	NC	–22.8	–21.3	–19.0
260–270	NC	–22.8	–22.5	–19.9
280–290	NC	–22.8	NC	–19.7
300–310	NC	NC	NC	–20.6
320–330	NC	NC	NC	–21.9

NA, Samples not analysed.
NC, Samples not collected.

observed between the soil profiles and the sediment lake core are due to the specific location of each sample: the middle of a big lake versus inside the vegetated area,with LCF50 in what is today the gallery forest, LCF150 in a dry forest and LCF200 in the dense woody savanna. A fall in lake level interpreted as a period drier than today, observed between 11 000 and 4500 yr BP (Sifeddine *et al*., 2003), is recorded as a three-stage process in the regional pollen record (Ledru *et al*., 2002). The $\delta^{13}C$ measured in the soil profiles, which were located further from the lake margins during this time of falling lake level and consequently suffered from a lack of soil moisture, confirm the presence of dry and open local vegetation near the lake during the early Holocene. Combining these three different types of

Table 4 ^{14}C dates of charcoal fragments found at distinct soil depths

Laboratory number[a]	Depth (cm)	Age (^{14}C yr BP)
TO-9145	30–40	1890±50
TO-9146	60–70	2560±60
TO-9147	80–90	3870±70
TO-9148	140–150	4580±70
TO-9149	230–240	8970±80

[a]TO, Isotrace Laboratory, Toronto, Canada.

results we are able to define accurately the evolution of a landscape undergoing climatic changes.

The palaeoenvironmental interpretations inferred from the sites close to the Lagoa do Caçó are in good agreement with the carbon SOM study from a 78-km forest–savanna ecosystem transect approximately 10 km distant from the Lagoa do Caçó (Pessenda *et al*., 2004b). Of seven sampling points, five indicate the predominance of C_3 plants and two a mixture of C_3 and C_4 plants during the late Pleistocene/early Holocene period. From approximately 9000 yr BP to *c*. 4000–3000 yr BP, the data indicate the significant presence of C_4 plants at most of sampling points. This was interpreted as a Cerrado (woody savanna) expansion probably resulting from a drier climate. From this period to the present, the SOM carbon isotope data became more depleted, indicating an increase in the presence of C_3 plants (higher arboreal density) in most of the ecosystem transect, probably resulting from a more humid climate, similar to the present-day conditions. Also using the SOM carbon isotopes, a very similar palaeovegetation pattern was observed during the Holocene in the southern part of the Amazon region, in a 400-km cerrado–forest transect in Rondônia State (Pessenda *et al*., 1998c) and in a 250-km savanna–forest transect in the southern Amazon State (Gouveia *et al*., 1997; Pessenda *et al*., 1998b, 2001b; Freitas *et al*., 2001), approximately 3000 km southwest of the Barreirinhas region. Similarly, at the Carajás site (Pará State, central Amazon region), approximately 1200 km west of the Barreirinhas region, a dry period was inferred from a sediment record in the interval 7000–4000 yr BP, as well as the development of forest vegetation thereafter (Sifeddine *et al*., 2001). Pollen analysis indicates the presence of a woody savanna from 7500 yr BP to the present, similar to that indicated by SOM carbon isotopes up to ~4000–3000 yr BP. After this, the carbon isotope data suggest an increase in arboreal density. This is associated with a moderate and progressive reforestation during the late Holocene period, not detected in the central sediment core of Lagoa do Caçó. Sedimentological studies in the Lagoa do Caçó confirm that Holocene climatic variations were not detected in the continuous central core (Sifeddine *et al*., 2003) and that from *c*. 5600 cal. BP (*c*. 4900 yr BP) environmental conditions approached those prevailing today (Jacob *et al*., 2004).

Holocene environmental conditions in the South American tropics

In South America important indications of fire are recorded from the beginning of the Holocene onward (Haberle and Ledru, 2001). Specifically in Brazil, very similar results were obtained in different regions (Pessenda *et al*., 1996b, 1998a,b,c, 2001, 2004a,b; Gouveia *et al*., 2002). During the early Holocene, between 10 000 and 7000 yr BP, solar forcing prevented forest from fully expanding in the tropics. The precession signal is characterized by warmer winters and cooler summers, and lower precipitation (Martin *et al*., 1997). Carbon isotopes point to a dominance of C_4 plants (grasses) in southern and southeastern Brazil (Pessenda *et al*., 1996a, 1998a, 2004a; Gouveia *et al*., 2002) and an expansion of savanna over the forest (from ~9000 yr BP up to ~4000–3000 yr BP) in the northwestern/northern (Amazon region) (Gouveia *et al*., 1997; Pessenda *et al*., 1998b,c, 2001b; Freitas *et al*., 2001) and northeastern regions (Pessenda *et al*., 2004b). Between 10 000 and 7000 yr BP, the pollen record shows an open landscape everywhere in the tropics south of the equator (Ledru *et al*., 1998) except for southern and northeastern part of Minas Gerais State, southeastern Brazil, where two pollen records attest to an expansion of the moist and cold forest and SOM carbon isotopes characterize the presence of a mixture of C_3 and C_4 plants (Pessenda *et al*., 1996b, 1998a). At Salitre, southern Minas Gerais, the cool rain forest progressively disappears in favor of a seasonal forest and an open landscape between 10 000 and 6000 yr BP (Ledru, 1993). The same pattern in the same time period, (a progressive change of rainforest to an arid lanscape) is also recorded at São Francisco Valley, Bahia State, northeastern Brazil (De Oliveira *et al*., 1999). Brazilian archaeologists observed an absence of records and sterile layers interbedded between the remains of two different hunting and gathering societies. This arid episode is roughly dated to 5000 yr BP (Schmitz *et al*., 1989). Two lacustrine records from the lowlands indicate a dry event at *c*. 5000 yr BP characterized by a sharp decrease in arboreal content, replaced by pioneer species such as *Piper* at Carajás (Absy *et al*., 1991) and dry herbs of the Asteraceae and Apiaceae families at Salitre (Ledru, 1993). Afterwards, progressive establishment of the modern vegetation is recorded until it became fully developed after 3000 yr BP.

The palaeoenviromental changes documented in Brazil during the Holocene have also been observed in lakes and ice core records in the high Andes. Between 10 000 and 8000 yr BP, Lake Titicaca (15°S latitude) became progressively drier. Between 8000 and 5500 yr BP the lake level increased to hydrological equilibrium and from *c*. 5500 and 3900 yr BP a drastic reduction in water level of *c*. 90 m is recorded, attesting to an abrupt dry event (Mourguiart *et al*., 1998; Baker *et al*., 2001). This extremely arid episode is also well recognized in Colombia at 5°N latitude (van Geel and van der Hammen, 1973). A hydrological model demonstrated that such a reduction can occur within a few hundreds years if the seasonality, and especially the rainfall distribution, is modified (Condom *et al*., 2005). After 3900 yr BP the return to moist conditions is recorded in the Lake Tititica basin (Mourguiart *et al*., 1998; Baker *et al*., 2001).

Concerning ice core records, $\delta^{18}O$ data from an ice core from Peru indicate climatic warming between 8200 and 5200 yr BP (Thompson *et al*., 1995). Although we need to be cautious with the dating, these studies confirm the strong impact of the early Holocene precession signal on climate and environment in tropical latitudes. On the other hand, we observe a difference in signal expression between the northern tropics and the southern tropics: at 10°N, the high-resolution laminated record of Cariaco point to an increase in precipitation and river discharge called the Holocene 'thermal maximum' between 10 000 and 7000 yr BP (Seltzer *et al*., 2000; Haug *et al*., 2001). This observation was recently confirmed by Ruter *et al*. (2004) in their model reconstruction.

The mid-Holocene is recognized as a period of particularly significant changes (Steig, 1999). Data from Antarctica and Greenland show a global decrease in atmospheric temperatures (Steig *et al*., 1997) while North Atlantic sea surface temperatures warmed and the tropical Pacific and Antarctic oceans cooled (Gagan *et al*., 1998) creating a dipole between Northern and Southern Hemisphere. The onset of the EL Niño–Southern Oscillation (ENSO) also dates from mid-Holocene, when seasonality became more contrasted and ITCZ seasonal shifts became stronger (Rodbell *et al*., 1999). Other regions, such as the one presented in this paper, did not record such an arid episode but a gradual expansion of woody vegetation after 7000 yr BP in the Cerrado area (Ledru *et al*., 2002). Therefore, the data reported in this paper indicate that the Lagoa do Caçó area represents an intermediate situation between the northern tropics and the Cariaco record, and the southern tropics of Brazil and Bolivia (see also

Seltzer *et al*., 2000). This situation could be explained by a weaker ITCZ seasonal shift maintained on a narrow latitudinal band.

Conclusions

Our results show that carbon isotopes are good indicators for regional palaeoenvironmental reconstructions and show a similar overall pattern of changes to the pollen records for the Barreirinhas region. They are also in good agreement with the other published records discussed previously.

Gaps, erosion or lack of sediment often prevent lacustrine records from defining accurately the early/mid-Holocene tropical dry period. Defining the spatial evolution of a landscape would require also much more coring than one from a single lake. In addition, lacustrine pollen spectra include pollen grains transported at a regional scale and, consequently, it is not possible to know about local surroundings' vegetation mosaics that form a landscape in the tropics. However, carbon isotope analysis, carried out in several profiles distributed along a transect, is able to recognize and describe the spatial dynamic of C_3/C_4 vegetation types in a wide area and on millennial timescales.

Our study shows that the latitude of Lagoa do Caçó probably represents an intermediate situation between the humid northern tropics and dry southern tropics during the early Holocene: at 10°N in the basin of Cariaco, the climate was very humid between 10 000 and 7000 yr BP and progressively dry after 7000 yr BP, while the reverse situation is recorded at 10–20°S, with a dry landscape between ~10 000 and 7000 yr BP becoming more humid between 7000–5500 yr BP, and very dry between 5500 and 4000 yr BP. At 5°S (our study area), we recorded a dry and open landscape from ~10 000 to 6000–5000 yr BP, becoming progressively more humid after ~4000 yr BP. These latitudinal differences in the expression of millenial-scale climatic changes during the Holocene are related to changes in the intensity and the displacement of the ITCZ in the tropics.

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