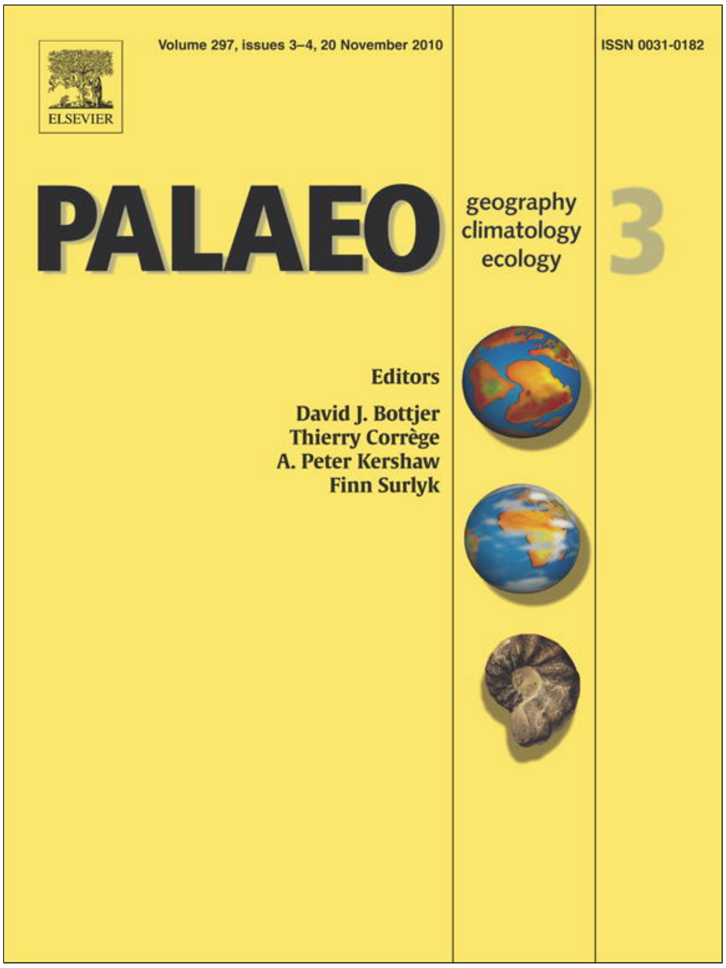
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Late Pleistocene and Holocene vegetation changes in northeastern Brazil determined from carbon isotopes and charcoal records in soils

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ABSTRACT

Northeastern Brazil represents a strategic area in terms of Quaternary records of environmental changes in South America due to its distinct semi-arid climate in near equatorial latitudes. In this study, carbon isotope and charcoal distribution records in soils are used to characterize vegetation dynamics, forest fires and their relation to climate change since the Late Pleistocene in the States of Ceará, Piauí and Paraíba, Northeastern Brazil. At the Ceará site, the carbon isotope record showed an enrichment trend from −24‰ to −19‰ during the early-mid Holocene, indicating an opening of vegetation and expansion of savanna vegetation (C_4 plants) during this period. A trend toward more depleted $\delta^{13}C$ values (~−32‰) in the late Holocene indicates an expansion of forest vegetation (C_3 plants). A similar trend is observed at the Piauí and Paraíba sites where values of ~−24‰ are associated with open forest vegetation during the late Pleistocene. In the early-mid Holocene, $\delta^{13}C$ values of up to −18.0‰ suggest the expansion of C_4 plants. Based on the carbon isotope data, it is postulated that from ~18,000 cal yr B.P. to ~11,800 cal yr B.P.–~10,000 cal yr B.P. arboreal vegetation was dominant in northeastern Brazil and is associated with humid climates. The savanna expanded from ~10,000 cal yr B.P. to ~4500–3200 cal yr B.P. due to a less humid/drier climatic phase, also supported by the significant presence of fires (charcoal fragments in the soil). From approximately 3200–2000 cal yr B.P. to the present, carbon isotope records suggest forest expansion and a more humid phase. These results form part of a regional pattern since they are in agreement with paleovegetation records obtained in regions of Maranhão, northeastern Brazil and in the Amazon and Rondonia States, northern Brazil.

1. Introduction

Important issues concerning the history of neotropics such as biogeographic patterns and past floristic connections and their relations to Late Quaternary climatic variations have been poorly addressed to date by paleocologists in northeastern Brazil. Nonetheless, there is strong evidence of the Atlantic rainforests having former connections with those of Amazonia (Andrade-Lima, 1982; Prance, 1985). In Northeastern this evidence has been supported by paleovegetation studies based on pollen, molecular and leaf fossil analyses (De Oliveira et al., 1999; Behling et al., 2000; Wang et al., 2004; Ledru et al., 2007).

In addition, paleoenvironmental studies in northeastern Brazil further our knowledge of the dynamics of the Inter Tropical Convergence Zone (ITCZ), an important atmospheric system that with insolation controls tropical climate variations (Martin et al., 1997; Ledru et al., 2002; Cruz Junior et al., 2009). Recently results obtained from speleothems attested contrasted climatic patterns along a north–south and east–west transect through South America, characterized by wet/dry climate in northeastern Brazil and dry/wet climate in southeastern Brazil. This general pattern is also confirmed by pollen analysis (Ledru et al., 2007). However pollen and speleothems show different results of the climatic patterns during the mid Holocene in Northeastern Brazil (Ledru et al., 2006; Cruz Junior et al., 2009) and during the glacial in southeastern Brazil (Cruz et al., 2005; Ledru et al., 2009). A wetter climate is attested by the speleothems while no main change in vegetation composition is recorded in the pollen analysis. A progressive expansion of the modern vegetation was observed due to the progressive increase of insolation values which modulated the latitudinal temperature gradient and the seasonal shifts of the ITCZ (Braconnot et al., 2007). More to the south, a pollen study of river valley deposits in the semiarid region of Bahia (De Oliveira et al., 1999) documented a humid and cold period during the Pleistocene/Holocene transition,

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which became progressively drier during the late Holocene. According to these authors, the presence of a modern day tropical forest with Amazonian and Atlantic Forest taxon is explained by enhanced humidity patterns during the early to mid Holocene. Studies on lake sediments from Lagoa do Caçó, Maranhão State (Ledru et al., 2001, 2002) attest late glacial high moisture rates until the end of the Pleistocene with the Younger Dryas (Ledru et al., 2002, 2006), also inferred from carbon isotopes of soil organic matter in a 80 km vegetation transect, 10 km far from Lagoa do Caçó (Pessenda et al., 2004a). Wetter conditions from ~20,500 cal yr BP to ~19,800 cal yr BP in the Caçó lake region, as shown by a 50% decrease in Deuterium/Hydrogen ratios and a marked increase in H isotopic fractionation of leaf waxes were reported by Jacob et al. (2007). Comparisons with other paleoprecipitation records from South American sites indicate late glacial humid conditions controlled by intensification of the ITCZ, and/or a southward shift of its mean position across the study site. The isotope data show only a small rise in aridity during the Younger Dryas event (13–11.5 ka) and D/H ratios of terrestrial and aquatic compounds show near constant offsets, suggesting stable and relatively humid climate conditions during this period. From the early to mid-Holocene, the Lagoa do Cacó level rose gradually despite the lower moisture availability and a distinct dry period until ~6950 cal yr BP (Sifeddine et al., 2003). Microscopic charcoal fragments found at this site during this period (Ledru et al., 2001) indicate interruption of the humidity by dry phases.

The use of carbon isotopes in studies of soil organic matter (SOM) dynamics has been used in different areas in Brazil to document vegetation changes during the Holocene period (Volkoff and Cerri, 1987; Victoria et al., 1995; Desjardins et al., 1996; Pessenda et al., 1996a,b, 1998a,b, 2001a; Freitas et al., 2001; Gouveia et al., 2002; Pessenda et al., 2004a,b, 2005). However, few studies using this approach have been developed in northeastern Brazil due to difficulties in finding preserved native vegetation areas, which are fundamental to the use of soil carbon isotopes in paleovegetation studies. The rationale behind the use of carbon isotopes in paleovegetation studies is well established.

In this paper, carbon isotope and charcoal records collected northeastern Brazilian soils are used to reconstruct vegetation changes and paleofire history and their relation to climate changes in this region. The soils were collected under natural vegetation in the States of Ceará, Piauí and Paraiba, covering a linear distance of ~900 km. The soil records also provide information on understanding the dynamics of the ITCZ and its seasonal displacement near the Atlantic Ocean and on the Amazon Basin border (Ledru et al., 2002; Sifeddine et al., 2003; Pessenda et al., 2004a), and document paleoenvironmental changes that significantly influenced the South American continent.

2. Study areas

The study sites are located in protected areas under the umbrella of the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA) in the northeastern region (Fig. 1, Table 1). The present study was developed at the National Forest of Araripe (FLONA), National Park of Sete Cidades (PARNA) and in the Biological Reservation of Guaribas (REBIO). The distance between these regions is ~500 km (FLONA-REBIO) and ~1400 km (REBIO-PARNA).

The FLONA site is located on the Araripe Plateau at 700–900 m elevation, between the coordinates 7°11′42″–7°28′38″S and 39°13′28″–39°36′33″W in the state of Ceará. Its forest vegetation is maintained by frequent humid winds and consequently by orographic rainfall, which according to Austregésilo Filho et al. (2001) is the main factor controlling the occurrence of these highland forest islands within the semi-arid realm of the Brazilian caatinga.

The soil in the study area is classified as Oxisol according to American Soil Taxonomy (USDA classification). The present climate is tropical, warm and humid and is defined as Aw' type according to Köppen classification. Mean annual precipitation values are ~1100 mm, and are concentrated in the rainy season (January to June) with maximum values occurring in March and April. The lowest precipitation values occur in October. The mean annual temperature is ~24 °C, ranging from 22.1 °C in the coldest month (July) to 25.8 °C in the warmest month (November) (Brasil, 1981).

Modern vegetation at FLONA consists of tropical rainforest, Cerrado (woody savanna), and "Carrasco", composed of trees of ~10 to 25 m in height with an arboreal density of ~1800 trees/ha. The latter is a closed, tall-shrubby, xerophilous vegetation community occurring on quartz sand soils between 700 and 900 m on Araripe and Ibiapaba plateaus in the Brazilian semi-arid domain (Araújo et al., 1999). The more important forest species are *Ocotea duckei*, *Parkia platycephala*, *Byrsonima sericea* and *Bowdichia virgilioides*. The Cerrado is characterized by herbaceous C_4 taxa such as *Aristida setifolia*,

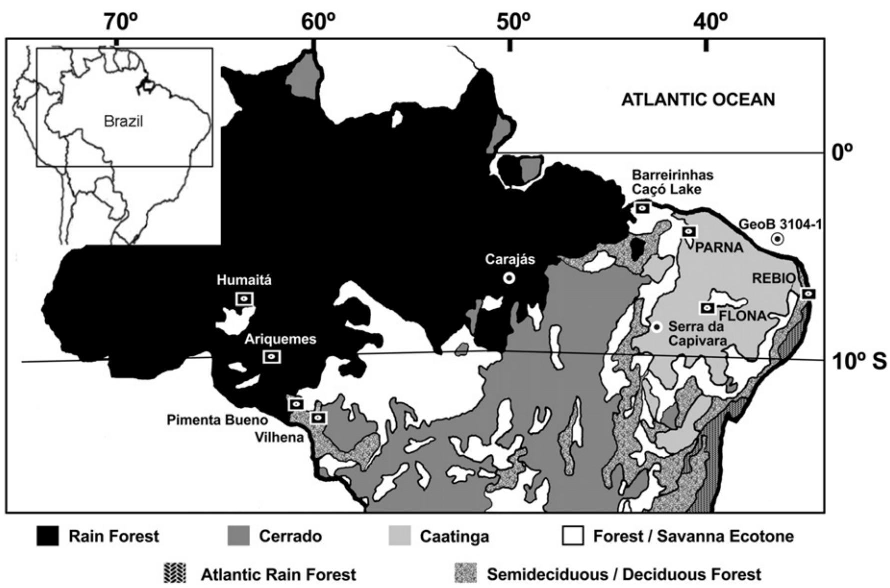

Fig. 1. Map of Brazil showing the present vegetation distribution in the Northeastern Brazil, the study sites (FLONA, REBIO, PARNA), previous study sites and analyzed materials (■ soil organic matter; ● lake sediment). Buried charcoal fragments were dated at Serra da Capivara.

Table 1
Vegetation types, sampling methods and geographic coordinates in the study areas.

Code site	Vegetation and sampling method	Latitude (S)	Longitude (W)	Altitude (m)	Location
km 0	Forest-trench	07°16′38.8″	39°27′05.5″	969	Flona
km 4	Cerrado-drilling	07°18′33.9″	39°27′46.5″	947	Flona
km 8	Carrasco-drilling	07°20′40.0″	39°28′54.1″	940	Flona
km 0′	Forest-drilling	07°14′12.1″	39°29′32.0″	982	Flona
km 6′	Carrasco-drilling	07°16′36.8″	39°31′26.9″	930	Flona
km 12′	Carrasco-drilling	07°14′24.4″	39°36′18.2″	920	Flona
I	Cerrado-drilling	04°07′30.5″	41°42′32.5″	239	Parna
II	Cerrado-drilling	04°07′48.8″	41°42′39.1″	240	Parna
III	Cerrado-drilling	04°07′52.3″	41°42′43.1″	246	Parna
IV	Cerrado-drilling	04°04′27.2″	41°43′42.5″	191	Parna
V	Cerrado-drilling	04°04′47.5″	41°42′14.2″	215	Parna
VI	Cerrado-trench	04°07′34.2″	41°42′34.8″	239	Parna
VII	Campo-drilling	04°05′46.8″	41°41′16.2″	178	Parna
VIII	Forest-drilling	04°05′41.5″	41°41′10.1″	182	Parna
I	Tabuleiro-drilling	06°41′25.4″	35°09′40.4″	157	Rebio
II	Tabuleiro-drilling	06°41′42.2″	35°09′44.1″	179	Rebio
III	Tabuleiro-drilling	06°47′49.8″	35°06′03.2″	128	Rebio
IV	Tabuleiro-drilling	–	–	161	Rebio
V	Forest-drilling	06°43′56.7″	35°10′28.3″	207	Rebio
VI	Forest-drilling	06°42′07.0″	35°09′41.0″	173	Rebio
VII	Forest-drilling	06°47′48.1″	35°05′56.3″	137	Rebio
VIII	Forest-trench	06°47′47.4″	35°05′59.1″	140	Rebio

Aristida adscensionis and *Aristida* sp, and C_3 and large arboreal taxa such as *Parkia platycephala*, *Caryocar coriaceum*, *Qualea parviflora*, *Simarouba amara*, *Himatanthus articulatus*, *Anacardium microcarpum* and *Ocotea duckei*. The predominant species in the Carrasco are *Maytenus* sp, *Copaifera langsdorffii*, *Miconia* sp and *Senna spectabilis*.

The second site, PARNA (7700 ha in area), is located the Sete Cidades National Park in northern Piauí State, at 4°05′–4°15′S and 41°30′–41°45′W. The present climate is tropical, warm and humid, and is defined as Aw' type according to Köppen classification. The mean annual precipitation is ~1200 mm, with the driest period occurring from July to December. The annual average temperature is ~25 °C. The soil is classified as typical quartzipsament according to the American Soil Taxonomy (USDA) (Brasil, 1981).

Apart from its geological attractions, Sete Cidades Park is known internationally for its pre-historic paintings, which were ^{14}C dated to ~6950 cal yr B.P. (Della Fávera, 1999).

Vegetation types at PARNA are forest, Cerrado (woody savanna) and Campo (open grassland savanna), with trees up to ~10 m in height and an arboreal density of ~800 trees/ha. The arboreal stratum is characterized by the families Fabaceae, Vochysiaceae, Malpighiaceae, Myrtaceae and Anacardiaceae and the herbaceous stratum is characterized by the Poaceae family, represented by C_4 taxa such as *Axonopus aureus* and *Axonopus* sp.

The third site, REBIO, is located within the Guaribas Biological Reserve in the State of Paraíba at 6°40′–6°45′S, 35°07′–35°12′W. Its climate is defined as As' in the Köppen classification system, i.e., warm and humid, with the dry season in the summer and rainy season during the autumn and winter. The average annual rainfall and temperature are 1750–2000 mm and 24–26 °C, respectively (Nimer, 1979). The studied area has a surface area of 3,994.2 ha with two rather different vegetation formations according to the phytoecological regions of Salgado et al. (1981): a semideciduous rainforest (Atlantic rainforest) of secondary formation and the open arboreal savanna, named "Tabuleiro". The Atlantic rainforest and Tabuleiro vegetation occur on red-yellow podzolic dystrophic soils and on quartz dystrophic sandy soils, respectively. The former is characterized by the presence of plant species such as *Andropogon bicornis* (Poaceae), *Stylosantes* spp (Fabaceae) and *Richardia grandiflora* (Nyctaginaceae). The dominant species in Tabuleiro are *Lagenocarpus* sp (Cyperaceae), *Aristida adscensionis* (Poaceae) and *Hancornia speciosa* (Apocynaceae). In northeastern Brazil, the denomination Tabuleiro represents areas near the coastline characterized by sandy lixiviated soils as well as savanna vegetation similar to the Cerrado (Rizzini, 1979; Oliveira-Filho and Carvalho, 1993). Tabuleiro vegetation seems to represent a transition between the open Caatinga and Cerrado formations and the Atlantic rainforest. The REBIO site presents the contact areas of the Cerrado vegetation with the seasonal rainforest, forming a mosaic ecosystem and representing an ecological gradient between these two types of vegetation, with trees up to 5 m in height and an arboreal density of ~500 trees/ha (Langguth, 1995). The REBIO site is located approximately 30 km east of the peripheral areas of the Caatinga, 20 km west of the Atlantic coast and 100 km south of the northern limit of the Atlantic rainforest (Por, 1992).

3. Sampling and methods

Soil samples were collected from trenches or by drilling up to 400 cm in depth on 2 sampling locations of 8 and 12 km in length at FLONA, 8 sampling locations at PARNA covering ~10 km and 8 sampling locations at REBIO covering ~14 km (Table 1). Sampling in trenches involved the collection of up to 5 kg of material at 10 cm intervals. Charcoal fragments present in each soil interval were hand-picked in the laboratory and their weight (g) was determined after removing the soil by physical treatment. After charcoal separation, soil samples were dried at 60 °C to a constant weight and no acid pretreatment was used.

For radiocarbon dating, the humin fraction of SOM, which is most likely the more stable and, theoretically, the oldest organic compound and thus representative of the soil age (Balesdent, 1987; Becker-Heidmann et al., 1988; Balesdent and Guillet, 1992; Pessenda et al., 2001b; Gouveia et al., 2002), was extracted using the chemical treatment described in Pessenda et al. (1996a,b). Charcoal samples with a mass >2 g were chemically treated by acid treatment with a heated (60 °C) 4% HCl solution for 4 h. The samples were then neutralized with distilled water and dried. Radiocarbon analysis was carried out at the CENA Radiocarbon Laboratory (Piracicaba, Brazil), following the standard procedure for liquid scintillation counting (Pessenda and Camargo, 1991). ^{14}C analysis on the small charcoal (<2 g) and humin samples was carried out at the University of Toronto Isotrace Laboratory using the accelerator mass spectrometry (AMS) technique. Radiocarbon ages are reported as ^{14}C yr (1σ) B.P. (Before AD 1950) normalized to a $\delta^{13}C$ of −25‰ VPDB and in calibrated years as cal yr (2σ) B.P. (Reimer et al., 2004) (Table 2). All results and discussions presented in the text are based on cal yr B.P. The charcoal radiocarbon ages represent a mean charcoal age for a soil layer that is 10 cm thick.

$\delta^{13}C$ analyses of modern vegetation (dominant plants) were carried out on leaves collected next to the sampling sites. The leaves were washed, dried at 50 °C, grounded, weighted (~1 to 2 mg) and analyzed.

For total organic carbon and $\delta^{13}C$ analyses on soils, the dry soil samples were sieved (210 μm), and root fragments were separated and weighted (up to 70 mg). Carbon analyses on soils and plants were carried out at the CENA Stable Isotope Laboratory (Piracicaba, Brazil) using an elemental analyzer attached to an ANCA SL 2020 mass spectrometer. Results are expressed in percentage of dry weight (total C) and as $\delta^{13}C$ with respect to the VPDB standard using the conventional δ (‰) notations.

$$\delta^{13}C(‰) = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \times 1000$$

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 soil grain size analyses were carried out at the Soil Science Department of the Escola Superior de Agricultura "Luiz de Queiroz"

Table 2
^{14}C ages of charcoal fragments and humin fraction (*) in relation to soil depth in three study sites.

Site	Depth (cm)	Laboratory number	Age (^{14}C yr B.P.), 1σ	Age (cal yr B.P.), 2σ
Flona (km 0)	60–70	TO-11879	2900 ± 60	2870–3220
	170–180	TO-12274	5780 ± 80 (*)	6410–6750
	270–280	TO-11880	11,280 ± 90	12,970–13,310
	330–340	TO-12275	8950 ± 90 (*)	9740–10,250
Parna (site VI)	90–100	TO-11813	3440 ± 60	3560–3870
	140–150	CEN-925	10,350 ± 90	11,950–12,420
Rebio (site VIII)	110–120	TO-11814	4660 ± 60	5290–5490

TO — Isotrace Laboratory, Toronto, Canada.
CEN — ^{14}C Laboratory, CENA/USP, Piracicaba, Brazil.
(*) — Humin fraction.

(Piracicaba, Brazil), University of São Paulo using the densimeter method (Kiehl, 1979).

4. Results

4.1. δ^{13}C data in plants

The δ^{13}C data at FLONA showed the arboreal species' δ^{13}C values ranging between −25.7‰ and −30.6‰ (typical of C_3 plants). The grass species *Aristida adscensionis* L. present in the forest and Cerrado areas also had typical values for C_3 plants (−32.7‰). At the PARNA site, the δ^{13}C values ranged from −26.7‰ to −33.1‰ for the forest arboreal species and from −11.7‰ to −13.5‰ for grass species of the Campo (savanna-like, C_4 plants).At the REBIO site, the δ^{13}C values of arboreal plants ranged from −22.1‰ to −32.4‰. Two grass species from the Tabuleiro area presented δ^{13}C values of −12.2‰ (*Paspalum* sp) and −32.4‰ (*Aristida setifolia* Kunth), respectively.

4.2. Soil properties and total organic carbon content

Depth profiles for clay content and total organic carbon in the studied soils are presented in Figs. 2 and 3. Grain-size analyses show that the soils at the FLONA sites are sandy-clay and clayey, with the clay component ranging from between 27% to 57%. The clay content at the PARNA locations is lower, ranging from between 4 to 14%, except at site VI (forest), which presents values from 27% to 61% at the 40–110 cm interval. At REBIO, soils in the forested areas are sandy (6–14% clay) in the shallow horizon and clayey (36–42% clay) in the deeper parts, while the soils under Tabuleiro are sandy (4–12% clay), sandy-loam (16–24% clay) and sandy-clay (34% clay). Carbon content data show a general decrease with depth, ranging from 5.2% in the shallow part of the soil to 0.2% in the deepest sample level at FLONA, from 0.8% to 0.1% at PARNA and from 3.1% to 0.2% at REBIO.

4.3. Radiocarbon dates on charcoal fragments and humin fraction

The ^{14}C dates for charcoal fragments and humin fraction of soil collected at FLONA (km 0–trench) are reported in Table 2 and Fig. 4. Charcoal samples indicated an age of ~13,200 cal yr B.P. at 270–280 cm and ~3100 cal yr B.P. at 60–70 cm soil depth. The humin samples produced radiocarbon ages of ~10,000 cal yr B.P. at 330–340 cm depth and ~6500 cal yr B.P. at 170–180 cm depth. The charcoal fragments collected at PARNA (Table 2 and Fig. 5) show ages of 12,200 cal yr B.P. at 140–150 cm and ~3700 cal yr B.P. at 90–100 cm depth. The charcoal fragment collected at REBIO showed an age of ~5400 cal yr B.P. at 110–120 cm depth (Table 2 and Fig. 6).

4.4. δ^{13}C data on soil organic matter (SOM)

For the interpretation of the SOM δ^{13}C profiles, it was assumed that variations smaller than 3‰ are associated with isotopic fractionation occurring during organic matter decomposition and with variations in the carbon isotope composition of atmospheric CO_2 (Boutton, 1996). Thus, variations in excess of 3–4‰ resulted from changes in plant community (Boutton, 1996; Desjardins et al., 1996; Pessenda et al., 1996a,b, 1998a,b, 2001a; Freitas et al., 2001; Gouveia et al., 2002; Pessenda et al., 2004a,b, 2005).

The δ^{13}C data on SOM are presented in Figs. 4 (FLONA), 5 (PARNA) and 6 (REBIO). The δ^{13}C values obtained in the surface soil samples showed a wide range that varied between −32.4‰ and −18‰. This

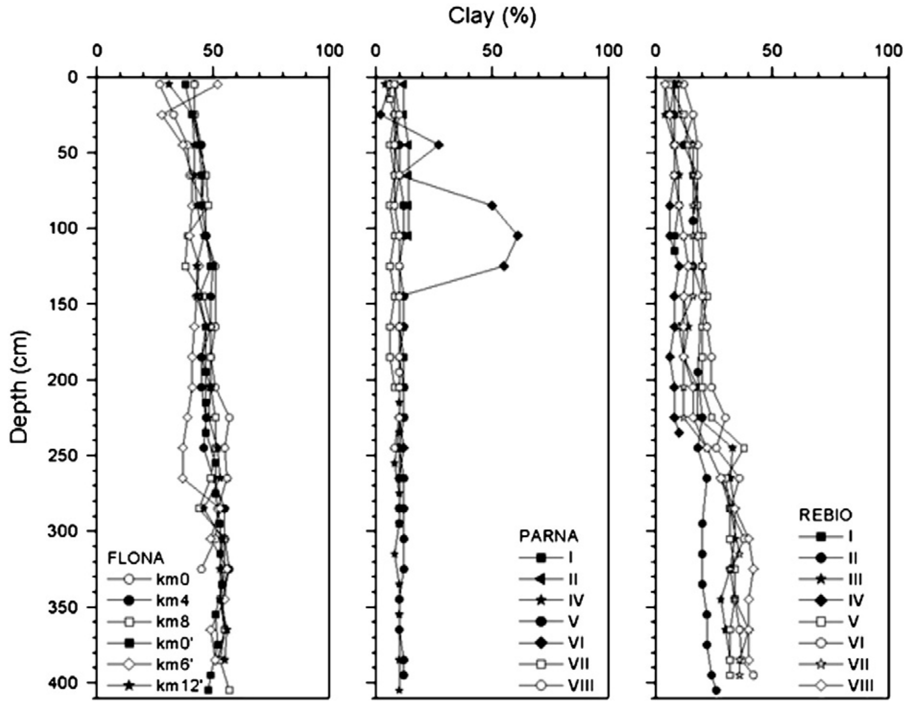

Fig. 2. Clay content of soils in relation to depth.

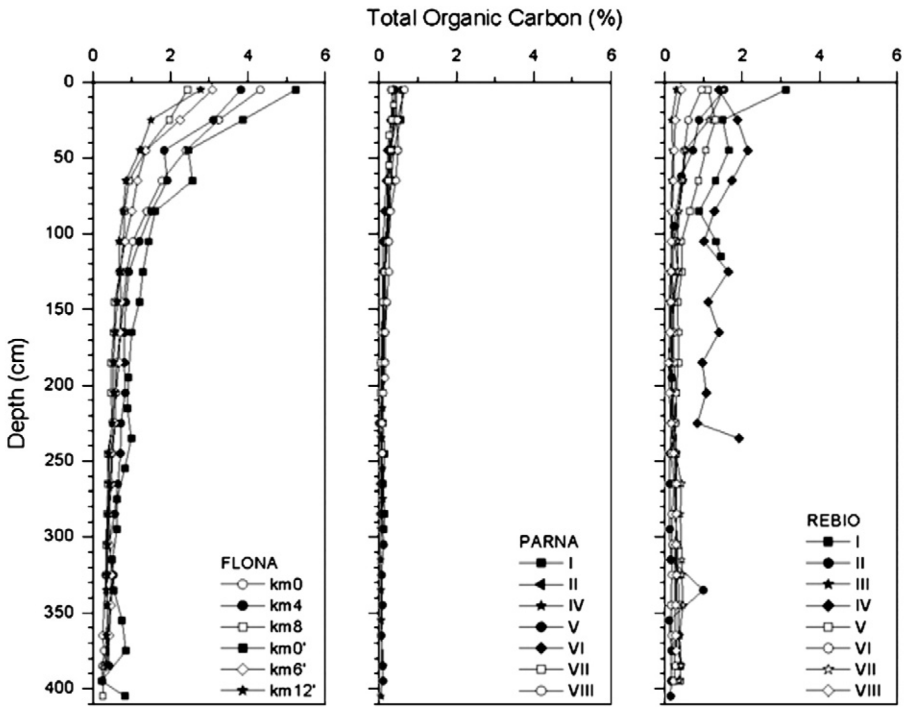

Fig. 3. Total organic carbon of soil organic matter in relation to soil depth.

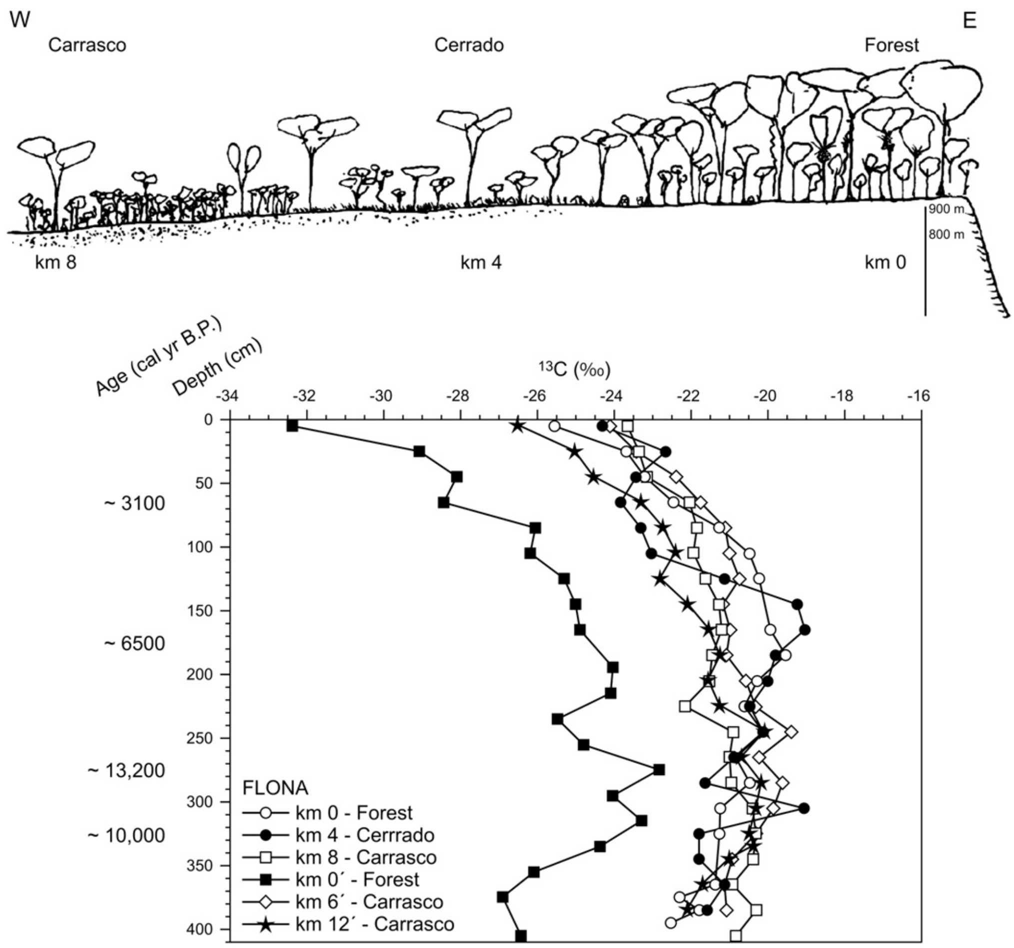

Fig. 4. $\delta^{13}C$ variation with soil depth of sampling points at FLONA and ^{14}C ages of charcoal fragments (*) and humin fraction (**) collected at km 0 (trench).

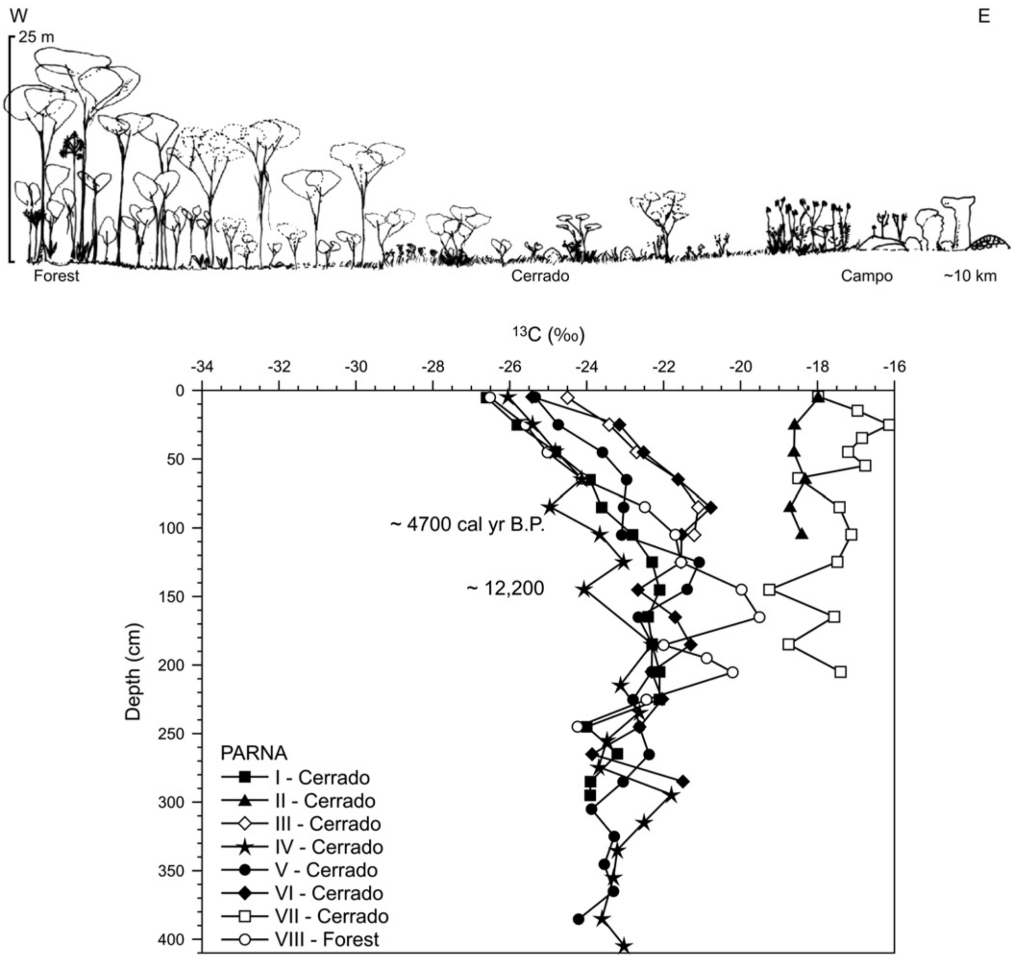

Fig. 5. $\delta^{13}C$ variation in relation to soil depth and ^{14}C dating of charcoal samples collected at site V in the PARNA area.

pattern is a reflection of the dominant vegetation type present in each sampling location. For example, the $\delta^{13}C$ value of −32.4‰ represents a denser forest vegetation type at FLONA (Fig. 4). The values between −24.5‰ and −26.6‰ are characteristic of less dense arboreal vegetation (woody savanna or Cerrado) still dominated by C_3 plants and the more enriched $\delta^{13}C$ value of −18‰ represents the grassland vegetation (Campo) at PARNA and reflects the significant presence of C_4 plants (Fig. 5).

The $\delta^{13}C$ profiles collected at FLONA (Fig. 4) showed a similar ^{13}C enrichment pattern with depth. The more depleted $\delta^{13}C$ values were observed in the denser forest site (km 0′). This profile showed a $\delta^{13}C$ value of −26.9‰ at a depth of 380–370 cm, changing to −22.8‰ and ~−24‰ at the internal 350–200 cm depth, followed by a trend to more depleted $\delta^{13}C$ values reaching a value of −32.4‰ in the soil surface over the interval of 200–0 cm. This significant $\delta^{13}C$ depletion of ~6‰ seems to occur after ~6950 cal yr B.P. The other soil profiles showed more enriched $\delta^{13}C$ values of ~−19‰ to −22.5‰ from the late Pleistocene/early Holocene to <6950 cal yr B.P. and a change to more depleted $\delta^{13}C$ values from −23.7‰ to −26.5‰ toward the surface. These patterns suggest that C_4 plants were the dominant plants in the Cerrado and Carrasco sites and they were also present in the current forest area at least from the late Pleistocene/early Holocene, after which C_3 plants started to dominate the entire area after ~6950 cal yr B.P.

The PARNA sites showed two distinct groups. One group, corresponding to Campo and Cerrado (site II), showed more enriched $\delta^{13}C$ values ranging between −20‰ and −16‰; this suggests the presence of more open vegetation since the late Pleistocene/Holocene period. The other Cerrado sites (second group) showed $\delta^{13}C$ values of approximately −22‰ to −23‰ during most of their early history; some showed a trend toward more enriched $\delta^{13}C$ values as high as −20.5‰ around 3800 cal yr B.P. (site VI). A similar pattern was observed in the forest site, which showed a shift from −23‰ to −19.5‰ and −21.5‰ from the late Pleistocene to mid Holocene periods. After ~5,900 cal yr B.P. a significant depletion of $\delta^{13}C$ values is observed in all sites, reaching values as low as −26.5‰ at the near soil surface. These patterns suggest that C_3 plants were the dominant plants in most of the area and C_4 plants were present in two locations in the studied period.

The REBIO location showed very significant ^{13}C changes in the Tabuleiro III and forest VIII sites, located 150 m apart, with $\delta^{13}C$ values of approximately −24‰ and −23‰ in the late Pleistocene/early Holocene period. A significant trend toward more enriched $\delta^{13}C$ values as high as −18.8‰ (forest site) and −16.5‰ (site III) is observed after ~10,000 cal yr B.P. (Fig. 6), suggesting the expansion of C_4 plants and an opening of vegetation in these areas. In the forest site (site VIII), a significant depletion to −26.5‰ was observed from ~2000 cal yr B.P. to the present, suggesting an increase in forest vegetation. $\delta^{13}C$ values at the other sites present a similar pattern (−22‰ to −24.5‰) until ~5900 cal yr B.P. and a change in values of −26‰ and −28‰ in the surface soil. These patterns indicate the predominance of C_3 plants in most of the sites and the expansion of C_4 plants with an opening of vegetation in two sites during the early to late Holocene.

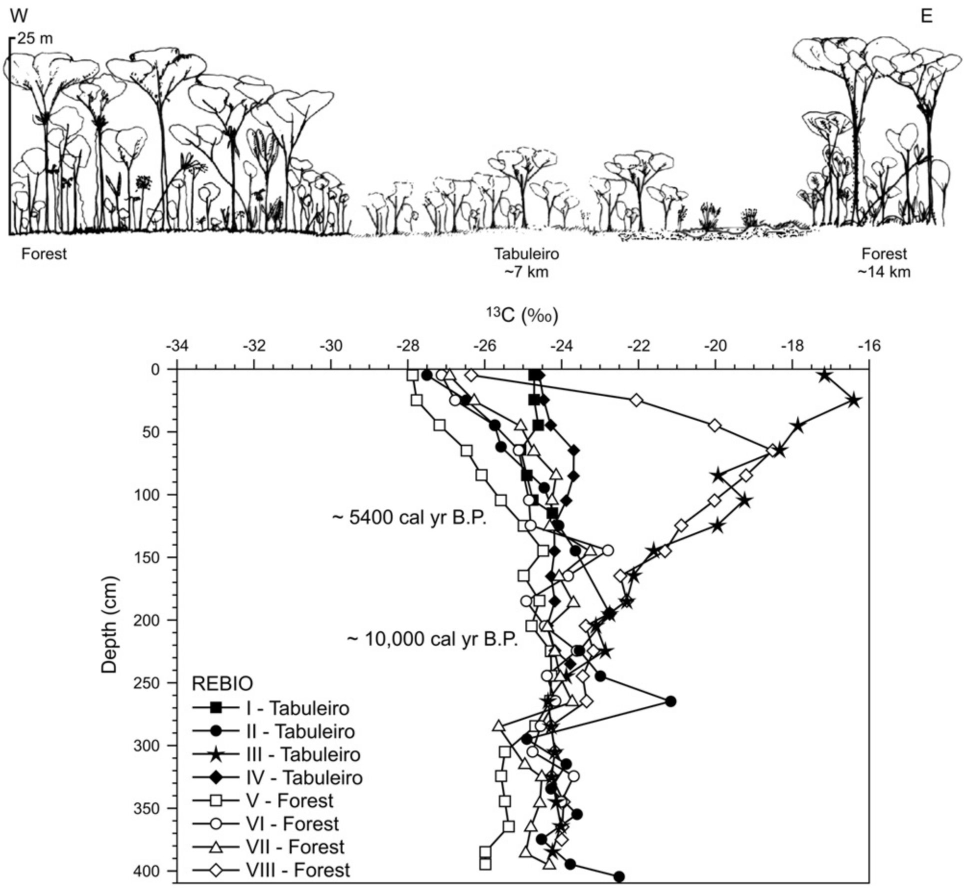

Fig. 6. $\delta^{13}C$ variation and ^{14}C dating of charcoal samples from the REBIO area.

4.5. Charcoal distribution in the soils

The three study areas show the presence of charcoal at different depths; higher concentrations are observed in the soil interval of ~200–150 cm to shallow depths (Figs. 7–9). The FLONA sites showed much higher carbon contents than the other regions (Fig. 3), reaching a peak charcoal concentration of ~12 g of charcoal/kg at the forest site (km 0′), which can be related to a

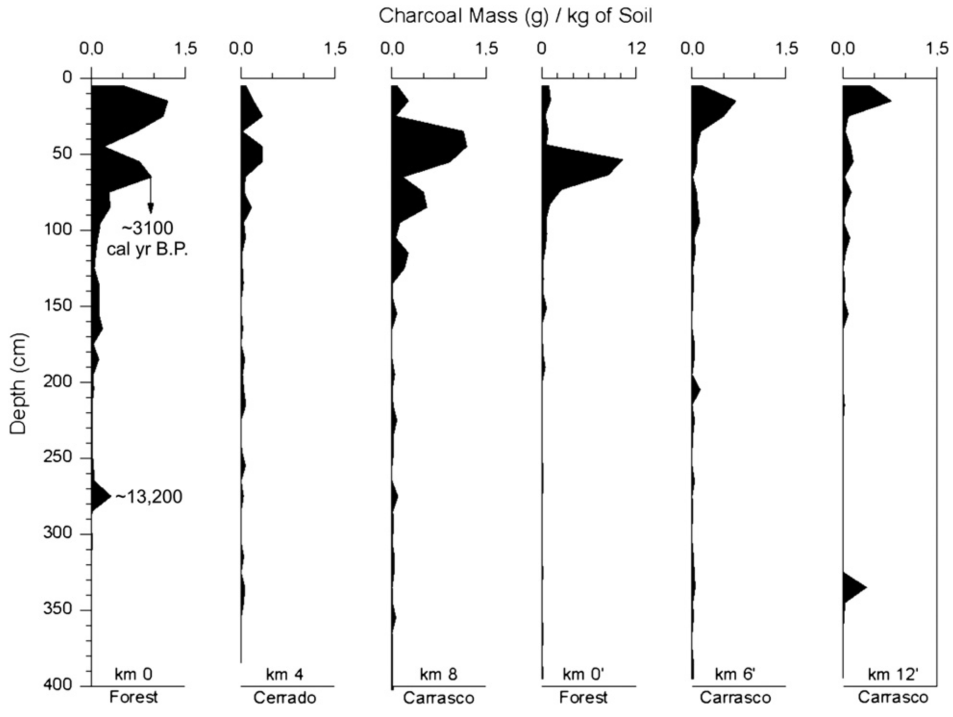

Fig. 7. Charcoal concentration with soil depth in the sampling sites at FLONA and ^{14}C dating.

higher vegetation density (inferred from the carbon isotope data) than the other sites.

At the PARNA sites, charcoal fragments were observed from 410–400 cm depth up to the surface (Fig. 8); higher concentrations tended to occur in the shallow layers (Fig. 8). The forest site showed higher carbon content (0.6 g/10 kg soil) compared to the Cerrado sites, which showed values lower than 0.5 g/10 kg soil. At the REBIO sites (Fig. 9), the carbon fragment concentrations were less than 0.5 g/10 kg soil; the highest charcoal amounts were found at site IV, covering the whole profile from 240 cm. Smaller amounts of fragments were found under forest vegetation, mainly from ~150 cm to the soil surface.

5. Discussion

Due to the very low C content of the soil in the study region (Fig. 3), only two ^{14}C dates were obtained for the humin fraction. The soils at Parna and Rebio are sandy and therefore present very low C concentration (Fig. 3), and after humin preparation ~90% of total organic C (fulvic and humic fractions) were extracted from the total soil. The only possible method to date samples with very small amounts (mg of C) is the AMS (Accelerator Mass Spectrometry). Samples from these two profiles were sent for analyses, however, no enough carbon was found for dating. The only possibility was to find and to date charcoal fragments and after several drillings and trenches in both sites, only two samples were found at Parna and one at Rebio. Both charcoal and humin fraction chronologies (Table 2) presented an age increase with depth (Balesdent, 1987; Becker-Heidmann et al., 1988; Balesdent and Guillet, 1992; Pessenda et al., 1996a,b; Saia et al., 2008) and are very similar to other records reported in distinct soils and locations in Brazil (Pessenda et al., 1998a,b; Gouveia and Pessenda, 2000; Pessenda et al., 2001a,b; Gouveia et al., 2002; Pessenda et al., 2004a; Souza-Júnior et al., 2007). The exception is the result of ~12,200 cal yr B.P. for charcoal fragments at 140–150 cm, which is much older than ages usually observed in other soils at similar depth. Considering the very small mass (less than 0.5 g) of the sample, the possibility of transport from deeper layers by soil fauna cannot be discarded (Boulet et al., 1995; Gouveia and Pessenda, 2000; Carcaillet, 2001a,b). Based on these age agreements with several soils and locations in Brazil, we consider the ^{14}C data presented in Table 2 to be representative of the soil organic matter chronology in all study sites. The age of the humin fraction at 170–180 cm (~6700 cal yr B.P.) is in agreement with charcoal and humin fraction dates at similar soil depths from other Brazilian regions (Pessenda et al., 1996a,b, 1998a,b; Gouveia and Pessenda, 2000; Pessenda et al., 2001a,b, 2004a,b). However, the humin at the 330–340 cm interval reveals a significantly younger age when compared to the charcoal sample at a depth of 270–280 cm (Table 2) in the FLONA profile. The charcoal fragments were dated ~13,200 cal yr B.P. and the humin ~10,000 cal yr B.P. Similar results were recorded in studies conducted in Central and Southeastern Brazil, where the charcoal ages were older than the humin ages for soil layers deeper than ~150 cm. In the first 150 cm, charcoal and humin samples showed similar ages, while in deeper soil profiles the charcoal was up to 27% older than the humin (Pessenda et al., 2001b; Gouveia et al., 2002). Despite these differences, an age estimate for the soil organic matter has been obtained using the buried charcoal fragments and/or the humin fraction. An age of ~10,000 cal yr B.P. was estimated for the 210–220 cm interval (Fig. 6) based on dating of charcoal fragments buried at similar soil depths (Freitas et al., 2001; Gouveia et al., 2002; Pessenda et al., 2004a,b, 2005).

The carbon isotope data showed a wide range of $\delta^{13}C$ values in specific regions and between regions. These patterns are a reflection of the distribution of C_3 and C_4 plants in each region, and are at least in part controlled by climatic conditions. The soil ^{13}C data obtained for FLONA and PARNA sites indicate that most of the Cerrado and one-forest sites were composed of C_3 and C_4 plants (isotope range from −20‰ to −23‰) during the late Pleistocene/early Holocene period. Some sites showed a trend toward more enriched $\delta^{13}C$ values, indicating a significant expansion of C_4 plants up to ~4500 cal yr B.P. In both regions, the isotope data showed that for most of their existence some areas have been covered by C_3 plants (forest site km 0′) or C_4 plants (sites II and VII). Both regions showed sites with a trend toward more depleted $\delta^{13}C$ values starting around 6900 cal yr

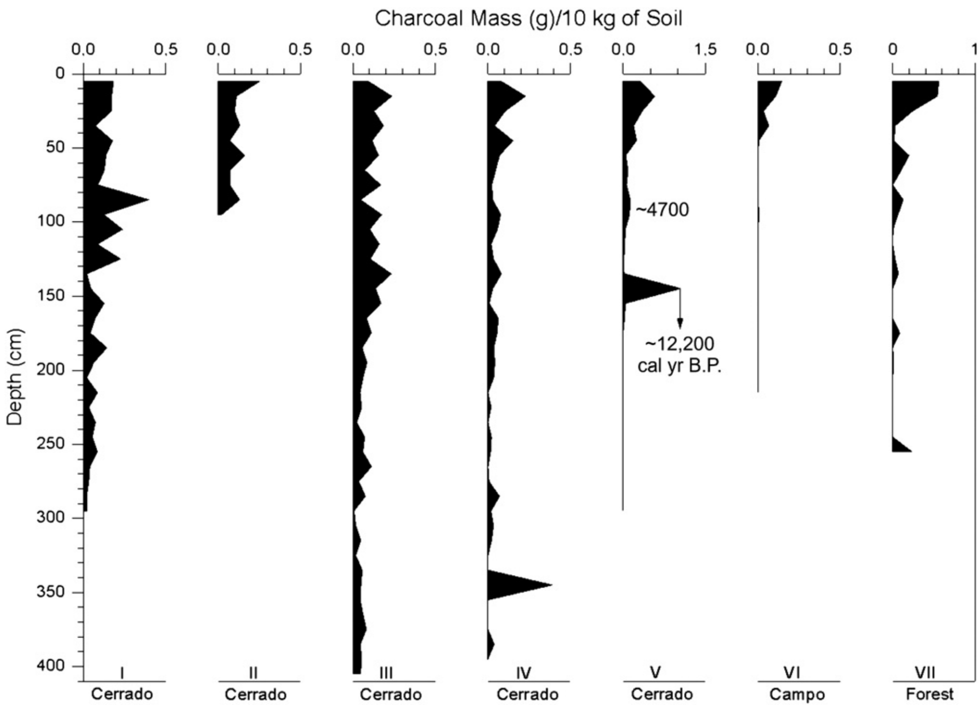

Fig. 8. Charcoal concentration with soil depth in the sampling sites at PARNA and ^{14}C dating.

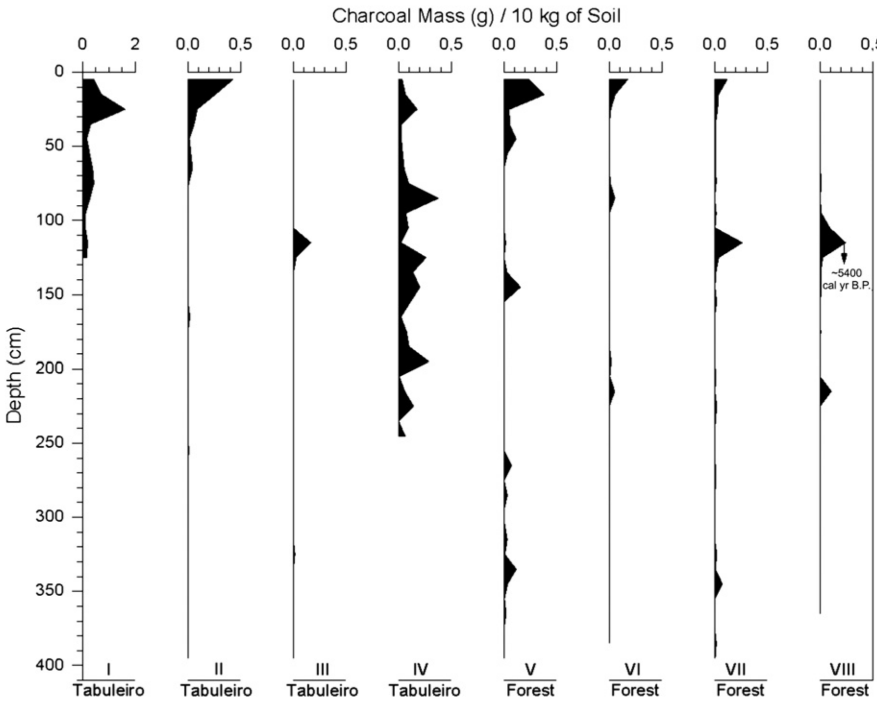

Fig. 9. Charcoal concentration with soil depth in the sampling sites at REBIO and ^{14}C dating.

B.P., implying a major shift toward the predominance of C_3 plants and reflecting a change toward more humid conditions. A more significant presence of C_4 plants in the mid Holocene, in areas presently covered by forests, suggests that the climate was drier (or less humid) than the present conditions in the FLONA and PARNA regions. The wide isotopic range observed in the shallow samples (from −24‰ to −32‰) reflects more open and denser forest conditions, respectively. At REBIO, the isotope data showed a significant change from more open forest (~−24‰) in the late Pleistocene to ~−18.5‰ and ~−16.5‰ in two sites; this indicates a change toward drier (or less humid than the previous period) conditions, with a maximum around 3200 to 2000 cal yr B.P. After this period, changes toward more depleted $\delta^{13}C$ values in six sites suggest a shift toward higher arboreal density, and are probably associated with more humid conditions.

The wide variability of the SOM $\delta^{13}C$ results in the same transect/region (C_3 plant dominance in determined sites or C_4 plant expansion in others) clearly highlights the importance of sampling representativeness. Therefore, in a paleovegetation/climate study with regional interpretations, it is important to consider the number and spatial distribution of points, regardless of whether the data comes from soil, peatland, lake sediments or cave speleothem records.

Buried soil charcoal fragments could also provide additional information about climatic conditions. The soil records indicate the presence of charcoal in all regions during at least the entire Holocene period, implying that fire was a common phenomenon and was more intense during the middle and late Holocene in the study region. This is clearly observed at FLONA sites, which have the highest charcoal concentrations compared to the other regions, with values of up to ~12–10 g/10 kg soil at the forest site (km 0′) around ~3200 cal yr B.P. The carbon isotope data suggest that forest vegetation composed of C_3 plants (trees) was always present at this site and became denser after 3200 cal yr B.P. A similar pattern is observed in other forest and Carrasco sites that presented lower charcoal content than the forest site at km 0′. The higher charcoal content obtained in SOM at km 0′ during this period can be related to the higher number of trees available in comparison to the Cerrado and Carrasco areas, which are characterized by more open vegetation. According to Stocks and Kauffman (1997), larger quantities of biomass are consumed in forests during the incandescent phase when combustion is less efficient, resulting in the production of greater amounts of charcoal. Similar charcoal patterns associated with paleofires have also been reported in several Brazilian soil sites (Pessenda et al., 1996b, 2001b, 2004a, 2005; Gouveia et al., 2002; Scheel-Ybert et al., 2003).

The occurrence of paleofires observed in the study areas during the entire Holocene period can also be associated with anthropogenic activities in addition to an eventual dry climate. Charcoal fragment ^{14}C dates from Serra da Capivara (Fig. 1) (~350 km from FLONA, ~500 km from PARNA and ~850 km from REBIO) range from 32,160 ± 100 ^{14}C yr B.P. to ~7000 cal yr B.P. (Guidon and Delibrias, 1986). While Holocene period radiocarbon dates are firmly accepted by the archaeological community, those of the Pleistocene period are not, as questions remain regarding the anthropogenic origin of charcoal and associated remains from this period. Based on archaeological results from the last three decades, data from distinct Brazilian (including the Northeastern region) and South American sites, and data from recent paleoenvironmental studies, Araújo et al. (2005–2006) suggest that larger areas of South America were mostly unoccupied by human groups during the mid-Holocene due to climatic stress associated with dry period events.

Based on data obtained at the study sites, it is possible to postulate that arboreal vegetation covered most of the study areas from approximately the late Pleistocene (~18,000 cal yr B.P.) to the late Plesitocene/early Holocene (~11,900–10,000 cal yr B.P.) periods. This timeframe is related to a more humid phase. From ~10,000 cal yr B.P. to 3200–2000 cal yr B.P. open vegetation (Cerrado/Tabuleiro) expanded due to the presence of a less humid climate. Charcoal data obtained at the study areas confirm the occurrence of fire and a less humid phase. The low charcoal content observed during this period could be explained by ecosystems with a predominance of thin fuel (grasses), as most biomass is burned during the flame emission periods (high combustion efficiency) and thus charcoal productivity is not significant and consists mainly of small particles (<1 mm) (Stocks and Kauffman, 1997). From approximately 3200–2000 cal yr B.P. to the present, a trend toward more depleted $\delta^{13}C$ of SOM in several points of the study areas was interpreted as an arboreal expansion, possibly a wooded cerrado (Cerradão) due to the return to a more humid phase which is similar to the modern climate. This is supported by the higher charcoal content obtained in SOM at the sites during the Holocene and mainly in late Holocene period at Flona site, as suggested by the higher number of trees (fuel) available in the forested vegetation (Figs. 4 and 7), in comparison to savanna areas observed at Parna (Figs. 5 and 8) and Rebio (Figs. 6 and 9) sites.

The paleoclimatic results of the studied areas are in agreement with most Late Pleistocene to Holocene paleoclimatic records from others areas of Northeastern Brazil. Carbon isotope records of SOM in a 78 km ecosystem transect in the Barreirinhas region (Maranhão State, ~300 km to 1500 km north of the study sites) indicate the predominance of C_3 plants in five sampling points and a mixture of C_3 and C_4 plants in two sites during the late Pleistocene/early Holocene period. From ~10,000 ^{14}C yr B.P. to ~4500–3200 cal yr B.P., data indicated a significant presence of C_4 plants at most sampling points. This was interpreted as a woody savanna expansion during the drier climate period. From this period to the present, SOM carbon isotopes became increasingly depleted of ^{13}C, indicating an increase in the presence of C_3 plants (higher arboreal density) in most of the transect as a result of a more humid climate similar to present-day conditions (Pessenda et al., 2004b, 2005).

In the same region of Maranhão State, palynological studies indicate that at ~18,000 cal yr B.P. the region of Caçó Lake (Fig. 1) was dominated by sparse and shrubby vegetation with a dominance of steppic grasses in poor, sandy soil. The landscape did not present any ecological characteristics of a modern Cerrado; however, single pollen grains of two Cerrado indicators, *Byrsonima* and *Mimosa*, suggest that some Cerrado species were able to survive, probably as small shrubs, under the prevailing dry climate. After ~14900 cal yr B.P., a sudden increase in moisture levels is evidenced with the progressive expansion of rainforest showing successive dominance of various taxa associations. The forest development ended abruptly between ~12,000 and 11,000 cal yr B.P., as attested by strong fires and the expansion of Poaceae. In the early Holocene an open landscape with relatively high lake water levels preceded the progressive expansion of Cerrado species towards a denser forested landscape; fires are recorded from then on, resulting in the physiognomy of the Cerrado known today. Late Pleistocene paleoenvironmental records from northern Brazil reflect the interplay between insolation forcing of two hemispheres with the local components represented by the interannual shift of the ITCZ and the influence of seasonal equatorward polar air incursions (Ledru et al., 2006). Sedimentological studies developed in a core from the margin of Caçó Lake show a decrease in sedimentation rates and a hiatus in the interval of 14900 cal yr B.P. to ~6500 cal yr B.P. Interpretation of these data suggest that the Holocene was characterized by lower moisture availability and a distinct drier period until ~6900 cal yr B.P. (Sifeddine et al., 2003).

At Icatu River, northern Bahia, ~500 km south of the FLONA site (Fig. 1), pollen analysis and radiocarbon dating of sediments (De Oliveira et al., 1999) suggest that the period between ~12,900 and ~10,000 cal yr B.P. was marked by very moist conditions, followed by a decrease in forest taxa and an increase of savanna. The period between 7800 and 7100 cal yr B.P. was possibly semi-arid, followed by moister climatic conditions between 7100 and 5400 cal yr B.P. The period between 5400 cal yr B.P. and the present mark a return to semi-arid conditions.

Marine pollen data (GeoB 3104-1) collected in the study area (Fig. 1) indicate the occurrence of Caatinga vegetation in northeastern Brazil during the recorded part of the Last Glacial and early Holocene periods (42,000 ^{14}C yr B.P.– 9400 cal yr B.P.), reflecting semi-arid conditions most of the time. The longer, wetter period was found from 18,500 to 12,800 cal yr B.P., which allowed for expansion of humid forests as indicated by expansion of the rainforest and humid mountain forests. A return to drier climatic conditions is indicated during the early Holocene (Behling et al., 2000).

In the Fernando de Noronha Archipelago (Fig. 1), State of Pernambuco, the geochemistry and isotope results in association with lithology and pollen analyses of sediment samples from Manguezal (mangrove) do Sueste indicate variations in the vegetation and location from the middle Holocene to the present (Pessenda et al., 2008). A significant sea level increase was recorded at ~6000 cal yr B. P. on the Brazilian coast (Suguio et al., 1985) and this event can be connected with the dynamic observed. In the same Archipelago, carbon isotopes of SOM indicate the predominance of C_3 plants since ~8400 cal yr B.P.

Based on the SOM carbon isotopes, a paleovegetation pattern similar to the present study was observed during the Holocene in the southern part of the Amazon region in a 400-km woody savanna-forest transect (Vilhena, Pimenta Bueno and Ariquemes, Fig. 1) in the State of Rondônia (Pessenda et al., 1998a) and in a 250-km savanna-forest transect (Humaitá, Fig. 1) in the southern Amazon State (Pessenda et al., 1998b, 2001a; Freitas et al., 2001). Similarly, at the Carajás site, central Amazon region, a dry period was inferred from a sediment record from 7900–4500 cal yr B.P., as well as the development of forest vegetation thereafter (Sifeddine et al., 2001).

Considering the results presented in this paper, the results of previous studies in the northeastern and Amazon areas, and the distances of ~2000 km to 3000 km between the study sites, it is possible to hypothesize that the high moisture rates of the late Pleistocene/early Holocene period (~18,000 to ~10,000 cal yr B.P) and the drier (less humid) early-mid Holocene period (~10,000 to 500–3200 cal yr B.P) was of regional scope and probably significantly influenced Brazil's northeastern and Amazon regions, confirming the phylogenetic analysis (Ledru et al., 2007).

Precipitation patterns between the end of the Pleistocene and the mid Holocene were strongly related to the position of the Inter-Tropical Convergence Zone (ITCZ) (Martin et al., 1997; Haug et al., 2001; Ledru et al., 2002) A southernmost position of the ITCZ during the YD chronozone is opposed to a northernmost position of the ITCZ at the mid Holocene 7000 to 5000 cal yr B.P. (Haug et al., 2001). However Northeastern Brazil is divided into two climatic regions which do not react to the ITCZ seasonal shifts in the same way because of the east-west precipitation gradient induced by the Hadley circulation (Diaz and Bradley, 2004). A second forcing on precipitation patterns is the summer monsoon influence. The eastern coastal region does not respond directly to the summer monsoon forcing although it can be affected by its intensity (Cruz Junior et al., 2009). Consequently when Amazon basin and surrounding regions experienced a short dry season, the eastern region records a long wet season from March to August (Hastenrath, 1990). The humid mid Holocene characterized by the speleothems analysis is neither characterized in the pollen nor in the isotope analyses. Cruz Junior et al. (2009) also wrote that no speleothem deposition was found in any cave between 15.1 and 13.2 kyr B.P. and inferred a dry episode related to the northern hemisphere Bolling-Allerod. However, here again, speleothems do not follow the change in vegetation which showed a moist forest development until the YD event, 12.7 kyr B.P.. We suggest that additional calibrations on speleothem responses to local changes in insolation, evaporation and precipitation rates are needed to explain, for instance, the absence of speleothem formation during a wetter-than-today climatic phase.

6. Conclusions

The carbon isotope variations observed in the study areas reflect changes in vegetation over the last ~18,000 cal yr B.P. Three major vegetation phases were identified: (i) a forest phase between ~18,000 and 10,000 cal yr B.P., (ii) woody savanna expansion between ~10,000 and 4500–3200 cal yr B.P., and (iii) forest expansion after 3200–2000 cal yr B.P. The presence of palaeofires reinforces evidence of a dry (less humid) early/mid Holocene period. This vegetation dynamic is similar to that observed in some regions of Maranhão (northeastern Brazil) and the Amazon and Rondonia States (northern Brazil), where forests were predominant during the late glacial period and savanna expansion was observed during the dry (less humid) and warm early/middle Holocene. After 3200–2000 cal yr B.P. similar forest expansion related to a moister period was observed, implying similar climatic conditions have affected these areas from the late Pleistocene to the present. This study emphasized that palaeovegetation/climate studies with regional interpretation inferred from soil, peatland, lake sediment and cave speleothem records require a sampling strategy that takes into account the spatial variability among different ecosystems, which can exist under the same climatic conditions in large extensions of land.

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