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Carbon isotopes in charcoal and soils in studies of paleovegetation and climate changes during the late Pleistocene and the Holocene in the southeast and centerwest regions of Brazil

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Abstract

This paper attempts to reconstruct vegetation changes and to infer climate changes during the late Pleistocene and the Holocene in the southeast (Botucatu, Anhembi and Jaguariúna, São Paulo State) and centerwest of Brazil (Pontes e Lacerda, Mato Grosso State). The research approach included the use of carbon isotopes (^{13}C and ^{14}C) in soil organic matter (SOM) and the evaluation of charcoal distribution and its identification at the species level. Soils sampled in this study were located under natural vegetation, along the slopes of small hills. Charcoal was found predominantly between 150 and 50-cm depth, indicating a period of greater frequency of fires in the study areas, between 6000 and 3000 years BP. For the Botucatu, Anhembi and Pontes e Lacerda sites, the δ^{13}C profiles suggest the predominance of C_3 plants during the entire Holocene. The ^{13}C patterns obtained at the Jaguariúna site that show a more significant presence of C_4 plants compared to the other regions, suggest that this region has been drier than the others during the Holocene. These patterns also indicate the presence of a drier climate compared with present-day conditions at the Jaguariúna region during late Pleistocene until the middle Holocene. This study shows the complexity of vegetation dynamics in the southeast of Brazil during the Holocene. It also shows that the analyses of multiple soil cores representative of the main vegetation communities are necessary for paleovegetation studies.

Keywords: ^{14}C dating; charcoal; soil organic matter; paleovegetation

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1. Introduction

The use of carbon isotopes in studies of soil organic matter (SOM) dynamics have been applied

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in different parts of the world to infer information about the link between vegetation and climate changes during the late Quaternary (Schwartz et al., 1986; Guillet et al., 1988). This approach had also been used in different areas in Brazil to document vegetation changes during the Holocene (Volkoff and Cerri, 1987; Desjardins et al., 1996; Victoria et al., 1995; Pessenda et al., 1996a,b, 1998a,b). The application of carbon isotopes is based on the different ^{13}C composition of C_3 and C_4 plants (Boutton, 1996) and its preservation in SOM.

The study of charcoal fragments found in sediments and soils also supplies information about climatic conditions. Charcoal species identification allows to characterize the vegetation that was present in the area (Scheel et al., 1995) and the amount distributed in the soil profiles can provide information about the occurrence of paleofires (Pessenda et al., 1996a). The presence of charcoal in soils under forest vegetation in Pará State (Soubiès, 1980), in the Upper Rio Negro, Amazon Basin (Saldarriaga and West, 1986) and in São Paulo State (Scheel et al., 1995), dated from middle Holocene to the present, indicate the occurrence of frequent fires in these areas, possibly associated with drier climate periods and/or human disturbance during the last 6000 years. In the case of central Brazil, a significant amount of charcoal was found in an oxisol soil under natural forest vegetation in the Salitre region. The charcoal distribution in the soil suggested that forest fires probably had an important role in determining the dynamics of forest vegetation during the Holocene. The δ^{13}C data indicate a probable mixture of vegetation since the early Holocene to ca. 1700 years BP in the Salitre area (Pessenda et al., 1996a).

In this paper, we report δ^{13}C data of SOM and ^{14}C dates on charcoal and soil humin from six soil profiles collected under natural vegetation in the São Paulo state, southeastern Brazil, and Mato Grosso state, centerwestern Brazil. The isotope approach was supported by an analysis of the charcoal distribution and by identification of charcoal fragments and its relation to the original vegetation. Carbon isotopes are used to evaluate vegetation changes during the late Pleistocene and Holocene and the occurrence of charcoal distribution is used to infer linkage between forest fires and climate changes.

2. Area descriptions, methods and material studied

The studied sites are located close to the cities of Botucatu (23°S; 48°W), Anhembi (22°45′ S; 47° 58′ W) and Jaguariúna (22°40′ S; 47°1′ W) in the São Paulo state, southeast of Brazil, and Pontes e Lacerda (15°16′ S; 59°13′ W) in the Mato Grosso state, southern Amazon region, centerwestern Brazil (Fig. 1). The soils of Botucatu and Pontes e Lacerda are developed on basalt and the soils of Jaguariúna and Anhembi on diabase.

The present climate in the study areas of the São Paulo state is subtropical. The average annual precipitation is 1314 mm in Botucatu, 1200 mm in Anhembi and 1410 mm in Jaguariúna. The annual mean temperatures are 19.4, 21 and 22 °C, respectively (Miklós, 1992; Mello et al., 1994). The Mato Grosso state (Pontes e Lacerda) is characterized by a tropical climate with an annual precipitation ranging from 1350 to 2000 mm and an annual mean temperature of 25 °C (Brasil, 1982).

The natural vegetation in all studied areas can be classified as semideciduous forest. In Botucatu, the forest is tall (3–27 m) and dry with a density of about 630 trees/ha. In Jaguariúna, the vegetation is lower (3–18 m tall) and the canopy more open (430 trees/ha). In Anhembi, the forest is the lowest (6–9 m tall) with a density of 1400 trees/ha. In Pontes e Lacerda, the trees are around 3–15 m tall and the vegetation is denser (870 trees/ha).

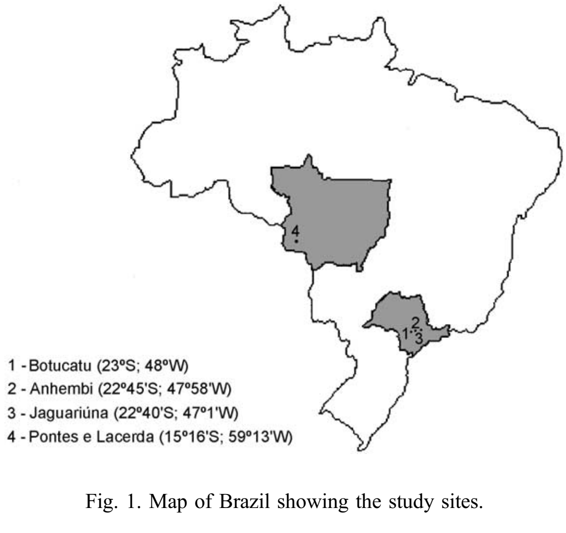

Fig. 1. Map of Brazil showing the study sites.

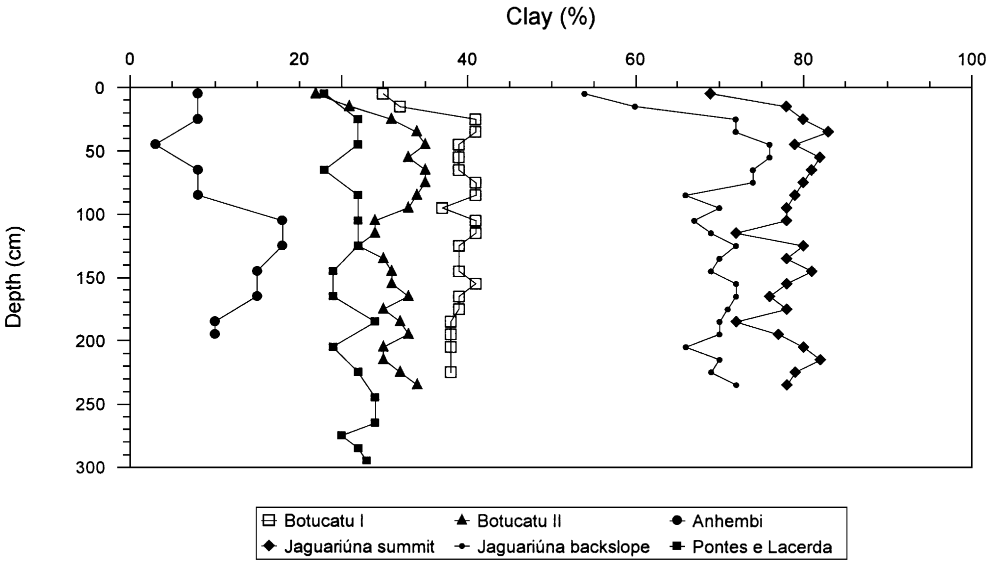

Fig. 2. Clay content of soils in relation to depth.

The two Botucatu soil profiles were collected from the top of two neighboring hills, separated by ~ 1500 m, and the soils are oxisols (USDA classification). In Anhembi, the sampling site was located at the top of a hill and the soil is an ultisol. The soils of Jaguariúna were collected in the same slope. One soil profile was sampled near the top, and is an oxisol. The other soil profile was collected 75 m downhill, and is an ultisol. The Pontes e Lacerda soil profile was collected near the top of a small hill and is an oxisol.

Soils were sampled at 10-cm intervals to a maximum depth of 250 cm. Samples were dried at 60 °C to constant weight, and root and plant remains were discarded by hand picking. Any remaining plant

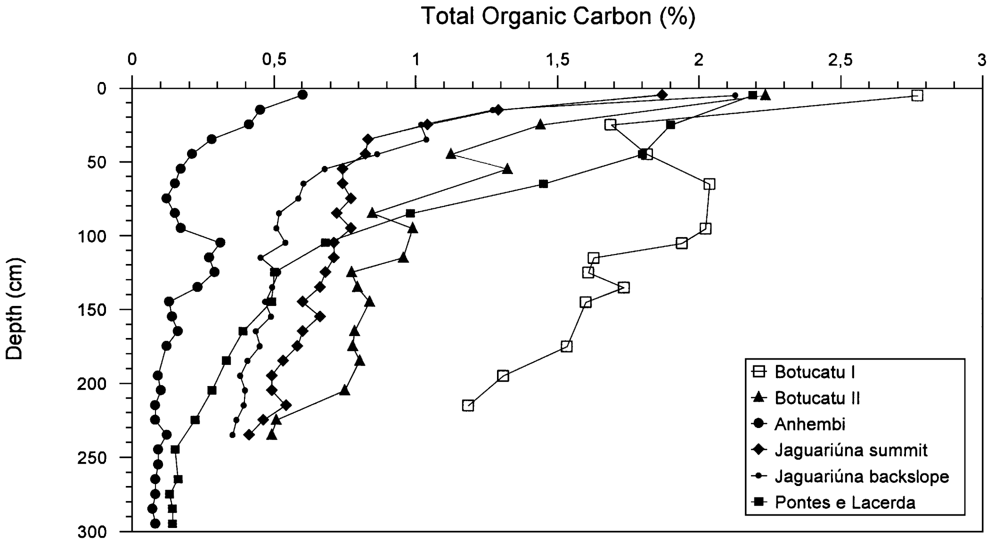

Fig. 3. Total organic carbon of soil organic matter in relation to soil depth.

debris was removed by flotation in 0.01 M HCl, then the soil was dried and sieved. The soil fraction finer than 0.210 mm was used for ^{13}C analyses and humin was extracted using a chemical treatment described in Pessenda et al. (1996a,b). ^{14}C analyses on the humin samples were carried out at the Isotrace Laboratory of the University of Toronto, employing the accelerator mass spectrometry (AMS) technique.

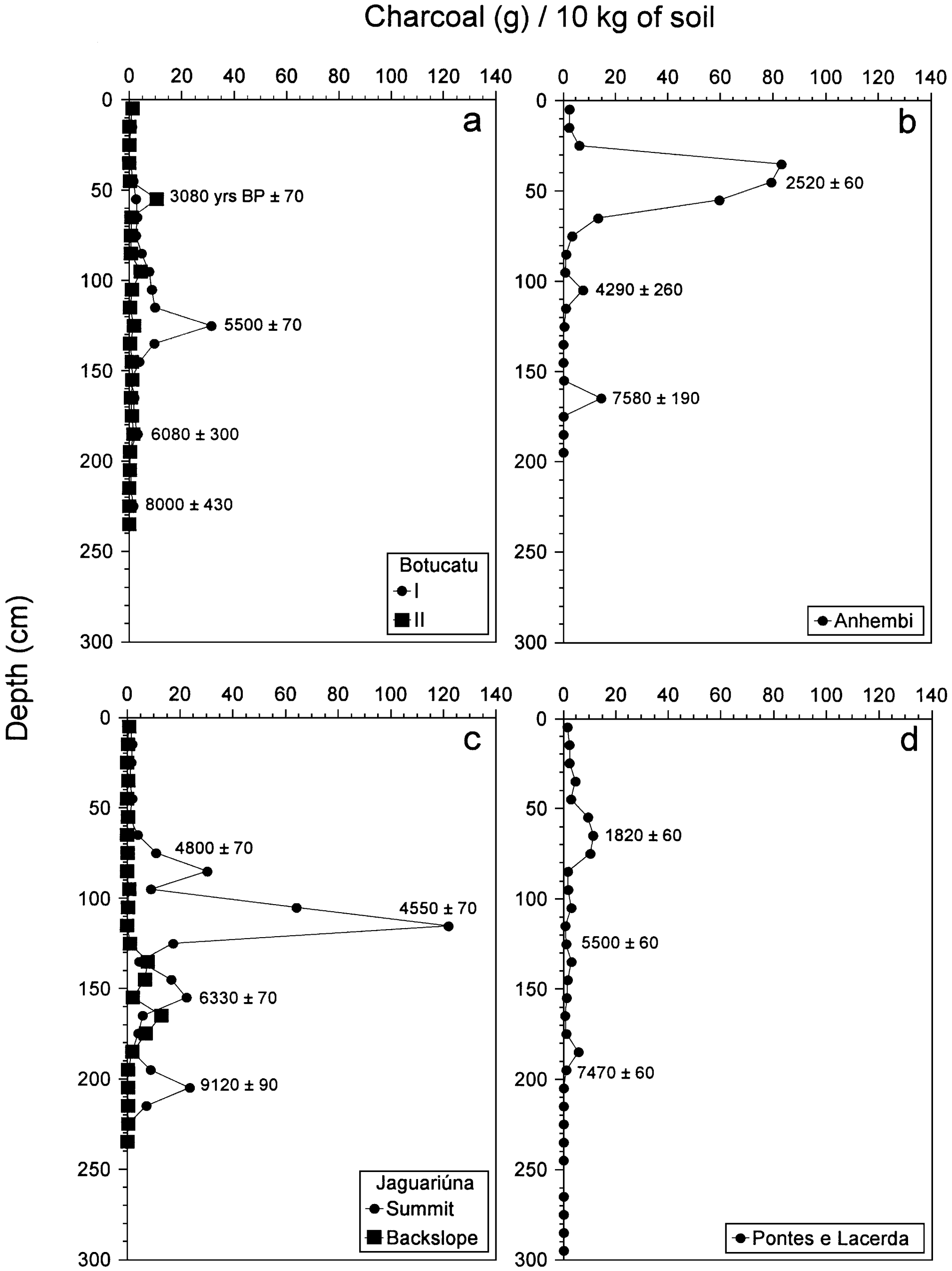

Fig. 4. Charcoal distribution with soil depth and the ^{14}C age of selected charcoal specimens.

The grain size analyses were carried out at the Soil Science Department of the Escola Superior de Agricultura “Luiz de Queiroz”, using the densimeter method (Kiehl, 1979). The ^{13}C analyses and total organic carbon were carried out at the Environmental Isotopes Laboratory, University of Waterloo, using a Carlo Erba Analyser attached to an Optima mass spectrometer. $^{13}C/^{12}C$ data are expressed in δ (‰) units relative to the VPDB standard, and organic carbon is expressed as percentage of dry weight.

Charcoal samples were collected by hand picking from soil samples and were subjected to the conventional acid–alkaline–acid treatment prior to ^{14}C analyses (Pessenda and Camargo, 1991). ^{14}C analyses were carried out at the Radiocarbon Laboratory, Centro de Energia Nuclear na Agricultura (CENA), following the standard procedure for liquid scintillation counting (Pessenda and Camargo, 1991). Small samples were analyzed at the Isotrace Laboratory of the University of Toronto by AMS technique.

Charcoal species identification was performed at the Laboratory of Paleoenvironment, Anthracology and Human Action, University of Montpellier II, France.

3. Results

3.1. Soil properties

The depth profiles for clay content and total organic carbon in the studied soils are presented in Figs. 2 and 3, respectively.

The soils at the Botucatu site are sandy-clay in the shallow horizon (30–32% clay) and clayey in the deeper part (38–41% clay) of soil profile I and sandy-clay (22–35% clay) in soil profile II. Soil organic carbon decreased from 2.8% at the surface to 1.2% at 220 cm in soil profile I. Soil profile II showed a carbon concentration of 2.2% at the surface decreasing to a value of 0.5% at 240 cm.

At the Anhembi site, the soil exhibited the lowest clay content. The soil is sandy in most of the profile (8–15% clay) and sandy loam (15–18% clay) from 100 to 170 cm. The carbon content decreased from 0.6% at the surface to 0.1% in the deeper soil horizon.

In Jaguariúna, the soils are more clayey. The topsoil profile exhibited a finer texture (64–85% clay) than the backslope soil profile (54–76% clay). Soil organic carbon ranged from 1.9% (top profile) to 2.1% (backslope) in the shallow soil horizons, decreasing to 0.4% in the deeper soil horizons.

The soil at Pontes e Lacerda is sandy-clay (27–29% clay), with some sandy loam layers (23–24%). The carbon content decreased from 2.2% at the surface to 0.1% at a depth of 290–300 cm.

Table 1
^{14}C ages of humin and charcoal in relation to soil depth at different study sites

Study Site	Depth (cm)	^{14}C age (years BP)		Difference [a] (%)
		Humin	Charcoal	
Botucatu I[b]	60–70	3930 ± 80[c]	3040 ± 180[c]	−23 (exception)
	80–90	–	4150 ± 110	
	100–110	–	4830 ± 70	
	120–130	5110 ± 60[c]	5500 ± 70	8
	180–190	6490 ± 120[c]	6080 ± 300[c]	concordant
	220–230	–	8000 ± 430[c]	
Botucatu II[b]	50–60	2490 ± 100[c]	3080 ± 70[c]	24
	90–100	3880 ± 50[c]	4630 ± 80[c]	19
	120–130	5010 ± 50[c]	5660 ± 270[c]	13
	180–190	6460 ± 70	4150 ± 450	−36 (exception)
	210–220	–	6690 ± 70[c]	
Anhembi[b]	40–50	2500 ± 60[c]	2520 ± 60	concordant
	60–70	2440 ± 60[c]	2700 ± 60	11
	70–80	–	2840 ± 120[c]	
	100–110	–	4290 ± 260	
	160–170	–	7580 ± 190	
Jaguariúna[b]	70–80	4770 ± 70[c]	4800 ± 110	concordant
	110–120	4840 ± 220[c]	4550 ± 70	concordant
	120–130	–	4770 ± 80	
	150–160	5820 ± 70[c]	6330 ± 70	9
	200–210	7490 ± 350[c]	9120 ± 90	22
	210–220	–	8660 ± 80[c]	
Pontes e Lacerda	40–50	–	650 ± 75	
	60–70	–	1820 ± 60	
	80–90	–	3960 ± 260	
	100–110	–	3630 ± 50[c]	
	120–130	–	5500 ± 60[c]	
	160–170	–	7220 ± 60[c]	
	180–190	–	6920 ± 60[c]	
	190–200	–	7470 ± 60[c]	

–, Non-analyzed samples.
[a] Relative to the humin.
[b] Pessenda et al. (2001).
[c] AMS.

3.2. Charcoal distribution in the soils

The four study sites show the presence of charcoal at different depths (Fig. 4). At the Botucatu sites, soil profile I showed the largest amount of charcoal in the 110–140-cm interval (50.6 g of charcoal/10 kg of soil). Smaller amounts were found in soil profile II, ranging from 10.5 g/10 kg of soil (50–60 cm) to 4.5 g/10 kg of soil (90–100 cm).

In the Anhembi soil, the largest amounts of charcoal were found in the 30–60-cm interval (83.3 and 59.6 g of charcoal/10 kg of soil). Smaller amounts were found at depths of 100–110 and 160–170 cm (7.5 and 14.4 g of charcoal/10 kg of soil, respectively).

The Jaguariúna soils also have significant amounts of charcoal, with the highest being 121.9 g/10 kg soil (110–120-cm layer) in the summit soil. In the backslope profile, charcoal was practically absent from the surface to 120 cm. The highest charcoal content was found in the 160–170-cm layer (13 g/10 kg soil).

The Pontes e Lacerda site exhibited the smallest amount of charcoal. The 50–80-cm soil interval produced 9.3–11.3 g of charcoal/10 kg of soil and 5.7 g of charcoal/10 kg of soil were found at a depth of 180–190 cm.

3.3. ^{14}C dating

The results of ^{14}C dating of the humin fraction of soils are listed in Table 1. These results were compared with radiocarbon ages obtained on charcoal samples collected at the same depths in order to evaluate and constrain the humin ages.

The humin ages show the typical profile of increasing age with soil depth. At the Botucatu sites, the radiocarbon ages ranged from ca. 2500 to ca. 6500 years BP. In Anhembi, the dates for the 40–70-cm interval are close to 2500 years BP. In Jaguariúna, the radiocarbon ages ranged from ca. 4700 to ca. 7500 years BP.

For the Botucatu sites, the charcoal ^{14}C data ranged from ca. 3000 years BP at 50–60 cm to ca. 8000 years BP at 220–230-cm depth. In Anhembi, the results ranged from ca. 2500 to ca. 4300 years BP in the upper 110 cm and ca. 7600 years BP at 160–170 cm. The radiocarbon data obtained at Jaguariúna summit soil ranged from 4800 years BP at 70–80 cm to ca. 8700 years BP at 210–220 cm. In Pontes e Lacerda, the ages ranged from ca. 650 years BP at 40–50 cm to ca. 7500 years BP at 190–200 cm.

The ^{14}C ages of humin and charcoal were in agreement at the 180–190-cm soil interval (Botucatu

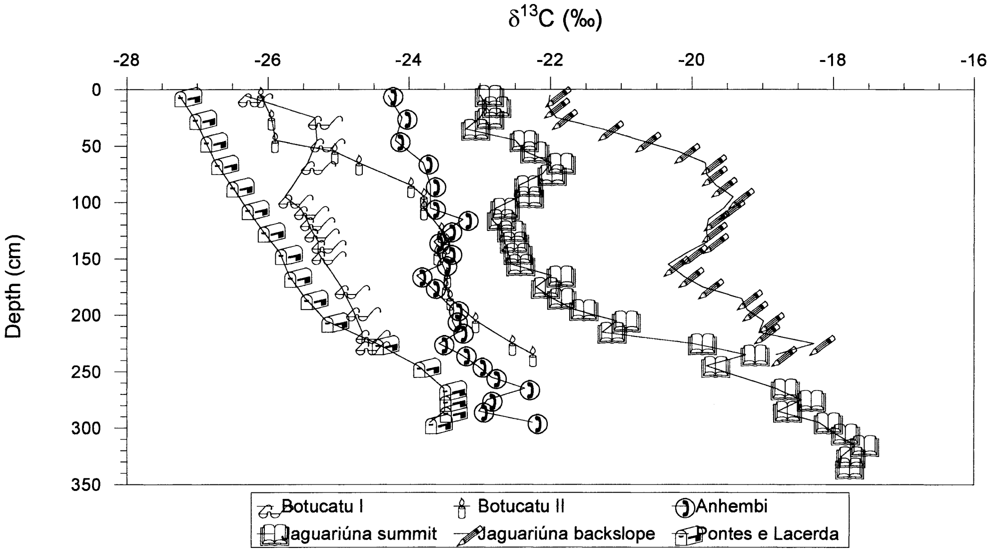

Fig. 5. δ^{13}C values of soil organic matter in relation to soil depth.

Table 2
Number of charcoal fragments identified from the Jaguariúna summit

			0–10 cm	50–60 cm	80–90 cm	100–110 cm	110–120 cm	190–200 cm	240–250 cm
Forest	Boraginaceae	*Patagonula americana*	1						
	Leg. Faboideae	*Centrolobium* aff. *tomentosum*	1	4					
Cerrado	Leg. Faboideae	*Acosmium* sp.							3
		Bowdichia sp.			6	1			
	Leg. Mimosoideae	*Plathymenia reticulata*				5	3		
	Vochysiaceae	*Qualea* spp.						4	
	Gramineae	Non-identified	1						
Forest or cerrado	Apocynaceae	*Aspidosperma* sp.	4						
	Leguminosae	Non-identified		1					
	Rubiaceae	Non-identified	1						
Non-identified (knots and bark)			2	1					
		Total	10	6	6	6	3	4	3

I), 40–50 cm (Anhembi) and at 70–80 and 110–120 cm (Jaguariúna). For the other seven soil intervals, the charcoal was 8–24% older than the humin. Only at the 60–70-cm depth in Botucatu I and at the 180–190-cm depth in Botucatu II, the charcoal was 23% and 36% younger than the humin, respectively.

3.4. ^{13}C results

The isotopic values (δ^{13}C) of soils in relation to the depth are presented in Fig. 5. The δ^{13}C values in the Botucatu soils ranged from − 26.3 ‰ at the surface to − 24.7 ‰ in the deepest part of soil profile I (210–220 cm). For soil profile II, the δ^{13}C values vary between − 26.1 ‰ at the surface and − 22.2 ‰ in the deepest part of the profile (230–240 cm).

At the Anhembi site, the δ^{13}C values show a trend toward more enriched values, varying from −24.3 ‰ at the surface to −22.3 ‰ at 300-cm depth.

At the Jaguariúna sites, the δ^{13}C values for the summit soil profile ranged from −23 ‰ to −21.1 ‰ in the upper 200 cm, tending toward more enriched values as high as −17.9 ‰ at 340-cm depth. In the backslope soil, the δ^{13}C values varies from −22 ‰ to −19.4 ‰ in the first 100 cm, decreasing to − 20.3 ‰ at 160 cm and becoming more enriched with depth, reaching a δ^{13}C value of − 18.8 ‰ at 240-cm depth.

In the Pontes e Lacerda area, the δ^{13}C values also show a trend toward more enriched values, varying from − 27.3 ‰ at the surface to − 25.2 ‰ at 200-cm depth and reaching a value of − 23.5 ‰ in the deeper soil horizon.

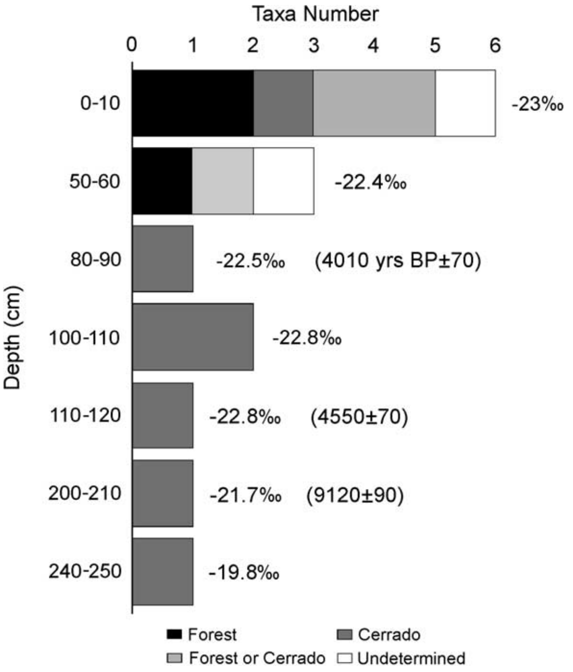

Fig. 6. Number of taxa of each vegetation type, radiocarbon dating of charcoal fragments and δ^{13}C values of soil organic matter in relation to soil depth of Jaguariúna summit profile.

3.5. Charcoal species identification

Anthracological analysis of charcoal collected at the Jaguariúna summit soil profile (Table 2 and Fig. 6) indicated an important contribution of forest taxa (*Patagonula americana*, *Centrolobium* aff. *tomentosum*) in the first 60-cm depth, corresponding to ages younger than 4000 years BP. From 60 to 250 cm (ca. 4000–9000 years BP), the charcoal analyses indicated the predominance of cerrado (wooded savanna) taxa (*Acosmium* sp., *Andira* sp., *Bowdichia* sp., *Plathymenia reticulata*, *Qualea* sp.) at the Jaguariúna summit site.

4. Discussion and conclusions

4.1. Carbon content and charcoal dynamics

The soil profile I at Botucatu shows a carbon content greater than 2.5% at the surface and a second peak (1.7% up to 2.0%) in the 50–120-cm interval, which seems to be related to the presence of a sombric horizon. The soil in the 50–120-cm horizon has a dark colour (Gouveia and Pessenda, 2000) that is probably connected with charcoal fragmentation during pedogenesis (Silva and Vidal-Torrado, 1999). A micromorphological study near the Botucatu I and II sites (Miklós, 1992) found charcoal fragments in the sombric horizon. The decrease of carbon with depth in the Anhembi, Jaguariúna and Pontes e Lacerda soil profiles is typical for soils in the Amazon Basin (Volkoff and Cerri, 1987; Desjardins et al., 1996; Pessenda et al., 1998a,b), São Paulo (Pessenda et al., 1996b) and Minas Gerais states (Pessenda et al., 1996a).

The presence of charcoal in the soils is indicative that the study areas have been affected by forest fires. The extremely high content of charcoal in some soil horizons indicates that fires were much more prevalent during some periods, perhaps indicating drier conditions (Pessenda et al., 1996a) and or human disturbance (Saldarriaga and West, 1986). The distribution of charcoal at distinct depths in Brazilian soils is related to the transport and surface accumulation of soil matter by the soil fauna (Boulet et al., 1995; Gouveia and Pessenda, 2000), a process that is well documented in tropical regions (Lee and Wood, 1971; Lavelle, 1983).

The period of higher amounts of charcoal in the Botucatu region, and of the most probable occurrence of fires, was dated to occur between ca. 3000–6000 years BP (Fig. 4, Table 1). The largest amount of charcoal (3.3 times) was found in soil profile I, which is about 1500 m from soil profile II. This pattern could be related to the presence of denser arboreal vegetation and/or higher intensity and frequency of fires, during the middle Holocene in the Botucatu site I compared to site II. δ^{13}C values of SOM, to be discussed later, provide information to test these hypotheses.

The higher occurrence of fires was dated between ca. 2300–2550 years BP in the Anhembi area. Considering that the ages are relatively recent, these paleofires could probably be related to the anthropogenic influence. Smaller amounts of charcoal indicated the presence of fires at ca. 4300 and 7600 years BP.

In the Jaguariúna soils, the highest abundance of charcoal found in the summit soil was dated to occur between ca. 4000 and 9000 years BP (Fig. 4). In the backslope soil, no charcoal fragments were observed from the surface to 120 cm. This aspect can be related to the presence of a Bt horizon (from 35 to 80 cm), which because of its high shrink–swell properties can pulverize charcoal during the burial mechanism (Gouveia and Pessenda, 2000). Considering that both profiles are separated by ~ 75 m, it can also be hypothesized that the largest amounts of charcoal found in the top profile could be related to a denser arboreal vegetation on the top of the slope. Similar to Botucatu, the δ^{13}C values, to be presented later, provide information to test this hypothesis.

In the Pontes e Lacerda, southern Amazon region, the probable period of higher frequency of fires was dated to occur between ca. 650 and 4000 years BP. More recent (younger) ages could be associated with the human disturbance. In the north central Amazon Basin, evidences of human presence at 1400 and 3750 years BP were described by Sanford et al. (1984).

The presence of a significant amount of charcoal in the 150–210-cm soil interval in Botucatu (180–190 cm), Jaguariúna summit (200–210 cm), Jaguariúna backslope and Anhembi (160–170 cm), Pontes e Lacerda (180–190 cm) could be indicative of a probable occurrence of paleofires during the early and middle Holocene in all study sites.

Comparing the four sites, it can be seen that significantly larger amounts of charcoal were found in the Jaguariúna region. This pattern can be associated with a high frequency and intensity of paleofires, probably related to a climate variation (drier period) between 4000 and 6400 years BP in the Jaguariúna region. The δ^{13}C values and preliminary charcoal analyses, to be presented later, provide information to test this hypothesis.

4.2. Comparison between the humin and charcoal radiocarbon ages

The charcoal radiocarbon ages were similar to and/or older than the humin ages, with the exception of two sets of data that show younger ages for the charcoal (Table 1). The Botucatu soil profile I shows a younger age (23%) for the charcoal in the shallow soil horizon and similar ages for both dated materials in the deeper soil horizons. The Botucatu soil profile II shows older ages (13–24%) for the charcoal compared to the humin fraction, apart from the deeper soil horizon where the ages are significantly younger (36%) for the charcoal. Perhaps, this fragment (less than 0.5 g) has been transported from shallow layers by soil fauna (Boulet et al., 1995; Gouveia and Pessenda, 2000). The ages for the charcoal and humin fractions of Anhembi are concordant in the shallow horizon. The 60–70-cm depth shows older ages for the charcoal (11%) compared to the humin fraction. In Jaguariúna, samples covering the first meter show similar ages for charcoal and humin fractions. Below 150 cm, however, the charcoal is up to 22% older than the humin.

In general, there was a good agreement between the ages of the humin fraction and buried charcoal in all the studied soils. This pattern has also been observed in other regions of Brazil (Pessenda et al., 1996a, 2001). This age comparison study shows that the humin fraction is a reliable material for ^{14}C dating of soil, devoid of charcoal. It is recommended, where possible, that both the humin fraction and charcoal should be dated in soil studies.

Based on charcoal ages, of further interest is the consistent soil matter surface accumulation rates of 0.24 mm year^{-1} in Botucatu I, 0.27 mm year^{-1} in Botucatu II, 0.23 mm year^{-1} in Anhembi and Jaguariúna and 0.32 mm year^{-1} in Pontes e Lacerda. These data are in very good agreement with the rates obtained in an oxisol soil in Salitre (0.21 to 0.23 mm year^{-1}), Minas Gerais state, central Brazil (Boulet et al., 1995; Pessenda et al., 1996a).

4.3. δ^{13}C soil profiles

In general, a ^{13}C enrichment trend with depth is observed in all the studied soils. However, significant δ^{13}C differences in absolute values are observed between sites and also within sites (Fig. 5). In the case of the Botucatu sites, no significant isotopic differences with depth are observed in the soil profile I. The δ^{13}C values ranged from -26.3‰ at the surface to -24.7‰ at 210–220 cm (Fig. 5). This ^{13}C-enrichment (1.6‰) with depth could be due to isotope effects occurring during decomposition of SOM (Nadelhoffer and Fry, 1988; Becker-Heidmann and Scharpenseel, 1992) and these isotopic signatures are typical for SOM generated by C_3 vegetation type (Boutton, 1996; Desjardins et al., 1996; Pessenda et al., 1996b, 1998b; Roscoe et al., 2000). The δ^{13}C values suggest a predominance of C_3 plants during the Holocene at this site.

The data collected at site II shows a different pattern characterized by a significant ^{13}C enrichment of 3.9‰ between the shallow soil horizon (-26.1‰) and the 230–40-cm soil depth (-22.2‰). In addition to the SOM isotope fractionation, the presence of a more open arboreal vegetation is another possibility for the ^{13}C enrichment. A relationship between higher/smaller arboreal densities and more/less negative soil surface δ^{13}C values was observed in a 250-km forest–savanna transect in the Humaitá region, southern Amazon state (Gouveia et al., 1997; Pessenda et al., 1998b; Freitas et al., 2001). The possibility of a more open vegetation could be associated with the presence of a dry climate, as described by Behling et al. (1998) in the Botucatu region. A pollen record from an organic rich headwater deposit shows a sedimentation gap from ca. 18,000 to 6000 years BP, which was related with dry climatic conditions that probably occurred during the early and middle Holocene. The presence of significant amounts of charcoal found in the soil of middle Holocene age, Fig. 4a, suggests high intensity and frequency of fires and also a probably drier climate in this region during this period.

It was postulated earlier that the highest amount of charcoal encountered at Botucatu I site during the middle Holocene, compared with Botucatu II site (Fig. 4a and b) was related to the presence of a larger density of trees in the later site. This hypothesis is supported by the information inferred from the $\delta^{13}C$ data. These data also indicated the predominance of C_3 plants during the whole Holocene in the Botucatu region, suggesting that an eventual drier climate in this region inferred from the fire history was not significant to change the vegetation ecosystem.

The $\delta^{13}C$ value in the shallow part of the soil profile at Anhembi (− 24.3 ‰) is characteristic of the modern vegetation cover, a semideciduous forest in which the dominant (75%) plant species (*Peschiera fuchsiaefolia*) showed $\delta^{13}C$ values varying from −29.1 ‰ to − 24.6 ‰. The litter showed a $\delta^{13}C$ of −27 ‰ (Gouveia, 2001). $\delta^{13}C$ value of around −25.0 ‰ in the first 100 cm indicated a change to a denser forest. The large amount of charcoal found at this depth (Fig. 4) also supports the presence of a dense forest at the Anhembi site.

The $\delta^{13}C$ values obtained at the Jaguariúna sites are clearly more enriched than the other sites from the São Paulo state. The soil profile collected on the summit of the slope showed a $\delta^{13}C$ value of −23 ‰ in the surface, characterizing the vegetation cover that is a less dense forest than in Botucatu. The most significant $\delta^{13}C$ change, − 22 ‰ to − 17 ‰, is observed in the soil interval 200–340 cm, indicating a major contribution of C_4 plants during the early Holocene and maybe late Pleistocene. Charcoal analyses of the Jaguariúna summit profile (Table 2 and Fig. 6) support the hypothesis that a drier climate occurred in Jaguariúna during the early to middle Holocene. Charcoal analysis from samples collected at 60- to 250-cm interval (4000–9000 years BP) indicated the exclusive presence of cerrado (wooded savanna) taxa.

The $\delta^{13}C$ data obtained at the Jaguariúna backslope site clearly shows a different pattern than the summit of the slope. The enriched $\delta^{13}C$ value of − 22 ‰ at the surface characterized an open vegetation cover similar to the summit site. The trend to more enriched $\delta^{13}C$ values from 40–50-cm layer (− 20.7 ‰) to 240-cm depth (− 18.8 ‰), clearly show a more significant influence of C_4 plants during the early to middle Holocene.

The different pattern, more depleted $\delta^{13}C$ values at the Jaguariúna summit of the slope location, up to 3.2 ‰ compared to the backslope sampling location separated by only 75 m, suggest a larger influence of C_3 in the summit site. This interpretation also agrees with the highest amount of charcoal found at this site (Fig. 4c), suggesting a more significant presence of C_3 plants this site in comparison to the backslope region during most of the Holocene. It is also clear that in the Jaguariúna region, the presence of C_4 plants was more significant during the early to middle Holocene, suggesting drier conditions.

The more enriched $\delta^{13}C$ values observed at Jaguariúna (higher C_4 influence) suggest the probable occurrence of a drier climate in this region during the whole study period from 8000 years BP. In addition, the highest amount of charcoal found in Jaguariúna may be related to a higher frequency and intensity of paleofires, supporting the existence of a drier climate.

Studies carried out in Londrina, state of Paraná, and Piracicaba, state of São Paulo, southeast region of Brazil, using an approach similar to that of the current study, indicated a predominance of C_4 plants in the late Pleistocene to middle Holocene, probably indicative of the presence of a drier climate (Pessenda et al., 1996b). In Salitre, state of Minas Gerais, central Brazil, the predominance of a mixture of vegetation since the early Holocene to ca. 1700 years BP was observed (Pessenda et al., 1996a). Pollen records in the south, southeast and central regions of Brazil also indicated the influence of a drier climate during this time (Behling, 1995a,b, 1997a,b; Ledru et al., 1998; Barberi et al., 2000).

The Mato Grosso site, Pontes e Lacerda, shows a $\delta^{13}C$ profile typical of C_3 plants in the first 200 cm (− 27.3 ‰ to − 25.2 ‰), representing the last 7500 years BP. The more enriched $\delta^{13}C$ values observed in the deeper soil horizons that also represent a predominance of C_3 plants could be due to isotopic fractionation associated to decomposition of organic matter and also to the presence of more open arboreal vegetation. Charcoal was found up to 200-cm depth, indicating a period of higher frequency of fires and a denser vegetation.

Significant variations in the densities of the native vegetation, probably related to the presence of a drier climate from early to middle Holocene, have also been reported in the north (Rondônia and Amazonas states) and south (Mato Grosso do Sul state) of Pontes e Lacerda site (Victoria et al., 1995; Gouveia et al., 1997; Pessenda et al., 1998a,b; Bezerra, 1999). The predominance of C_3 plants inferred from the ^{13}C data at the Pontes e Lacerda area suggests that the vegetation in these areas was not significantly influenced by these climatic variations.

Similarly, several $\delta^{13}C$ soil profiles from a 250-km transect located in Humaitá region, south of the Amazonas state, indicated that the savanna vegetation was present in most of the studied locations during the stage of forest regression between about 8000 and 4000 years BP, probably due to drier climatic conditions. However, in the extreme points of this transect (kilometers 5 and 250), the presence of this vegetation type was not observed, suggesting that some locations were not significantly influenced by the same dry climatic conditions, despite a relatively short distance and the similar environmental and edaphic characteristics (Pessenda et al., 1998b; Freitas et al., 2001). Furthermore, the same tendency was observed during the early to middle Holocene in a transect of about 500 km in the Rondônia state (200 km south of Humaitá). Replacements of C_3 by C_4 plants were observed only in the southern part of the state, while in the northern area (closer to Humaitá region), forest vegetation prevailed during the whole Holocene Epoch (Pessenda et al., 1998b).

The study reported in this paper clearly shows the complexities of vegetation response to eventual climate changes. It also shows the need for the collection of multiple cores representing the different vegetation communities in the studied region, in order to infer a better understanding of past vegetation changes and their relation to climate changes.

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