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Holocene fire and vegetation changes in southeastern Brazil as deduced from fossil charcoal and soil carbon isotopes

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Abstract

Carbon isotopes of soil organic matter (SOM) and radiocarbon dating on charcoal from nine soil profiles collected under native forest vegetation in Londrina, state of Paraná, Anhembi, Botucatu and Jaguariuna, São Paulo and Salitre, Minas Gerais, southeastern Brazil, were used to evaluate the vegetation changes and to establish the chronology. ^{13}C and ^{14}C data in SOM and charcoal, respectively, indicate that C_4 plants were the dominant vegetation in Londrina and Jaguariúna during the Late Pleistocene until Middle Holocene, probably associated with the presence of a drier climate. In Anhembi and Botucatu, C_3 plants dominate the landscape during the period. A probable mixture of C_3 and C_4 plants occurred in Salitre during the Holocene. This study is part of a main research program related to palaeoenvironmental reconstruction of vegetation and climate in distinct regions of Brazil during the last 20,000 years.

1. Introduction

Several approaches that include geomorphological (Ab'Saber, 1977, 1982; Servant et al., 1981; Bigarella and Andrade-Lima, 1982), biological (Haffer, 1969; Prance, 1973; Gentry, 1982), palynological (Absy et al., 1991; Ledru, 1993) and isotopic studies (Martinelli et al., 1996; Pessenda et al., 1996, 1998a, b) have been used to infer past climatic changes in Amazonia, and central, southeastern and southern regions of Brazil. An understanding of the degree to which these changes affected the composition of the soil organic matter (SOM) improves our ability to understand changes in the future.

The use of carbon isotopes in studies of SOM dynamics has been applied to infer information about vegetation and climate changes during the Late Quaternary (Schwartz et al., 1986; Guillet et al., 1988; Pessenda et al., 1996). This approach has also been used in different areas in Brazil to document vegetation changes during the Holocene (Volkoff and Cerri, 1987; Victoria et al., 1995; Desjardins et al., 1996; Pessenda et al., 1996, 1998a, b, 2001a; Gouveia et al., 1997) and Late Pleistocene/Holocene (Freitas et al. 2001).

The application of carbon isotopes is based on the different ^{13}C composition of C_3 and C_4 plants and its preservation in SOM. ^{13}C values of C_3 plant species range from approximately −32‰ to −20‰ PDB, with a mean of −27‰. In contrast, $\delta^{13}C$ of C_4 species 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, 1991).

The study of charcoal fragments found in sediments and soils also supplies information about climatic conditions. Charcoal distribution in the soil profiles can provide information about the occurrence of paleofires (Pessenda et al., 1996). 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), in São Paulo (Scheel et al., 1995) and Minas Gerais (Pessenda et al., 1996), southeastern Brazil, indicate the occurrence of frequent fires in these areas, possibly associated with drier climate periods and/or human disturbance during the last 9000 yr.

In this paper we report $\delta^{13}C$ data of soil and ^{14}C dates on charcoal from nine soil profiles collected under

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natural vegetation in the Paraná, São Paulo and Minas Gerais, southeastern Brazil. The isotope approach was supported by an analysis of the charcoal distribution. Carbon isotopes are used to evaluate vegetation changes during the Late Pleistocene and Holocene, and the occurrence and dating of charcoal distribution are used to infer linkages between forest fires and climate changes and to establish the chronology.

2. Area descriptions, materials, and methods

The study sites are located near the cities of Londrina (23°18′S, 51°10′W), Paraná state, Piracicaba (22°43′S, 47°38′W), Botucatu (23°S; 48°W), Anhembi (22°45′S; 47°58′W), Jaguariúna (22°40′S; 47°1′W), São Paulo state and Salitre (19°S, 46°46′W), state of Minas Gerais, southeast of Brazil (Fig. 1).

In all areas, the present climate is subtropical. The average annual precipitation is around 1200 to about 1400 mm. The annual mean temperatures are around 19.4–22°C (Miklós, 1992; Mello et al., 1994). The natural vegetation in all studied areas can be classified as semideciduous forest.

The soil in Londrina is an Alfisol (USDA classification). In Piracicaba it is an Oxisol, and samples were collected at the top of a slope. The two Botucatu soil profiles were collected from the top of neighboring slopes, separated by ~1500 m, and the soils are Oxisols. In Anhembi, the sampling site was located at the top of a slope and the soil is an Ultisol. The soils of Jaguariúna were collected from the same slope. One soil profile was sampled near the top, and is an Oxisol. The other soil profile was collected 75 m down the backslope, and is an Ultisol. Soil samples in Salitre were collected from three excavations ca. 250 m apart in the same slope and the soil is an Oxisol (Pessenda et al., 1996).

Soils were sampled at 10 cm intervals to a maximum depth of 340 cm, dried at 60°C to constant weight, and root and plant remains were discarded by handpicking. Any remaining plant debris was removed by flotation in 0.01 M HCl, dried and sieved. The soil fraction less than 0.210 mm was used for ^{13}C analyses.

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 PDB standard and organic carbon is expressed as percentage of dry weight. The analytical precision was 0.2‰ and 2%, respectively, for three sample repetitions.

Charcoal samples were collected by handpicking from soil samples and were submitted to the conventional

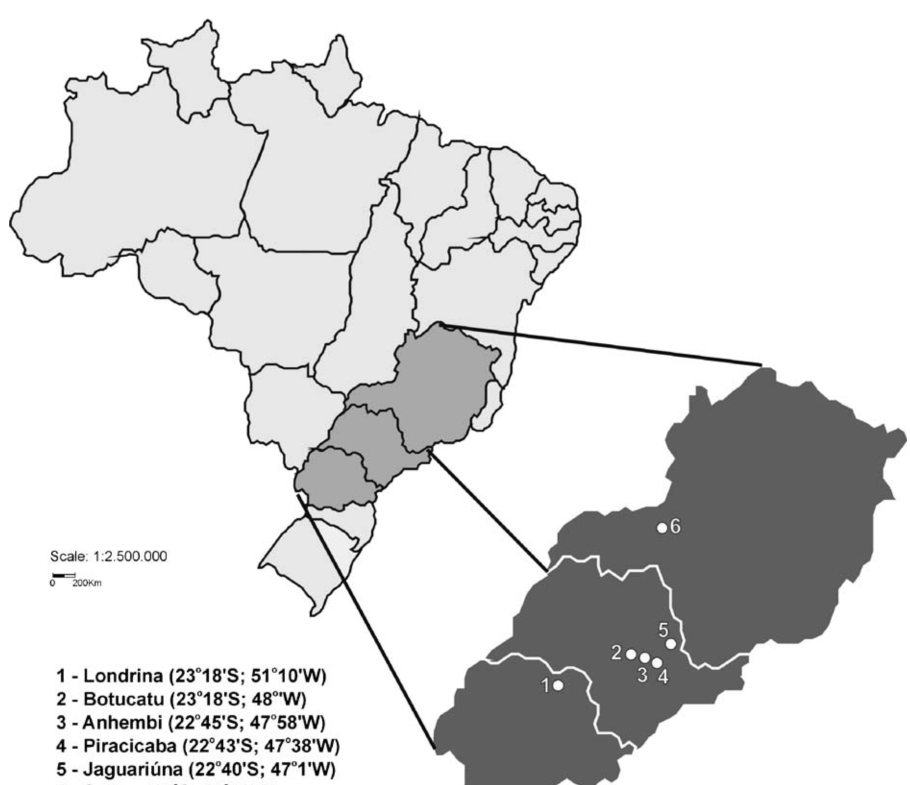

Fig. 1. Map of Brazil showing the study sites.

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 using AMS.

3. Soil properties

The clay content and the total organic carbon of soils in relation to the depth are presented in Figs. 2 and 3, respectively. The soils at Londrina and Piracicaba sites are clayey (42–79%) as described by Pessenda et al. (1998c), as well as in Salitre (77–85%). The soils at the Botucatu site are clay-sandy in the shallow horizon (30–32%) and clayey in the deeper part (38–41%) of the soil profile I and clayey-sandy (22–35%) in the soil profile II. In Anhembi, the soil presented the lowest clay content. The soil is sandy in most of the profile (8–15%) and sandy loam (15–18%) from 100 to 170 cm. In Jaguariúna, the soils are more clayey. The upper soil profile presented a more fine texture (64–85%) than the backslope soil profile (54–76%).

The total organic carbon content decreased from the shallow soil horizons to the deeper part of the profiles as observed in other studies in Brazil (Pessenda et al., 1996; Pessenda et al., 1998a), indicating the highest values (6.7–1.6%) in the Salitre profile. In Londrina, the values changed from 1.9% to 1.0% and in Piracicaba from

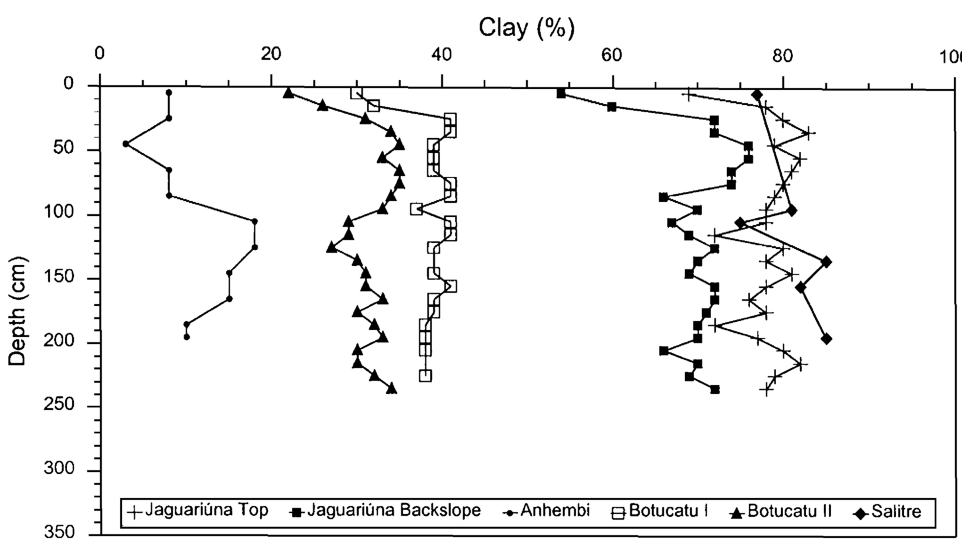

Fig. 2. Clay content of soils of the study sites.

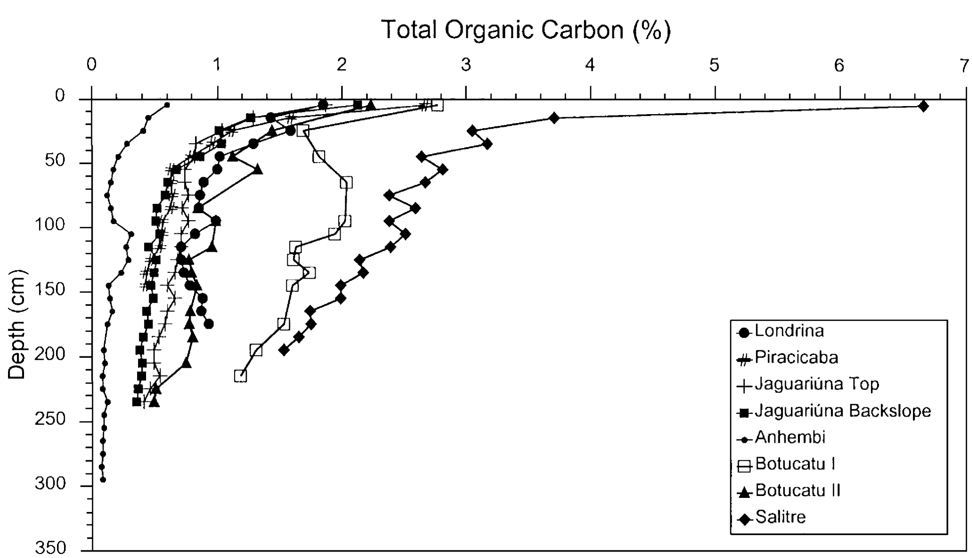

Fig. 3. Total organic carbon of soil profiles.

2.7% to 0.6%. In Botucatu, the organic carbon content decreased from 2.8% at the surface to 1.2% at 220 cm in soil profile I. Soil profile II presented a carbon concentration of 2.2% at the surface, decreasing to a value of 0.5% at 240 cm. In Anhembi, the carbon content decreased from 0.6% at the surface up to 0.1% in the deeper soil horizon. In Jaguariúna, soil organic carbon ranged from 1.9% (top profile) and 2.3% (backslope) in the shallow soil horizons, decreasing to 0.3% in the deeper soil horizons. Considering that most of the soils are clayey Oxisols with the presence of buried charcoal, the high carbon content in the Salitre site is probably due to its very denser vegetation cover, which supplies the soil surface with higher biomass and consequently higher carbon content.

4. Charcoal distribution in the soils

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) and is well documented in tropical regions (Lee and Wood, 1971; Lavelle, 1983). In previous studies, good agreement is observed in general between the ages of the humin fraction of SOM and buried charcoal, related to soil depth in distinct regions of Brazil (Pessenda et al., 1996; Pessenda et al., 2001b). In this study, we used the ^{14}C dates of charcoal fragments to establish the chronology. These age comparison studies showed that the humin fraction is also a reliable material for ^{14}C dating of soil, devoid of charcoal (Pessenda et al., 2001b).

Charcoal is present along the entire soil profile in most locations (Fig. 4). Some high peak contents (up to 120 g of charcoal/10 kg of soil in Jaguariúna) are observed at certain soil depths, without a clear relationship among the locations. The presence of charcoal in these soils is a clear indication that the study areas in Botucatu, Anhembi, and mainly Jaguariúna and Salitre have been affected by forest fires, probably for most of their history. The extremely high charcoal content in some soil horizons indicated that these events were much more severe during some periods, maybe indicating much drier conditions. Saldarriaga and West (1986) also associated the presence of charcoal in the soil with possible dry periods and/or human disturbances in the regions of Colombia and Venezuela, Amazon Basin. The ^{14}C dates ranged from 6000 BP to the present and the ages were coincident with dry phases recorded

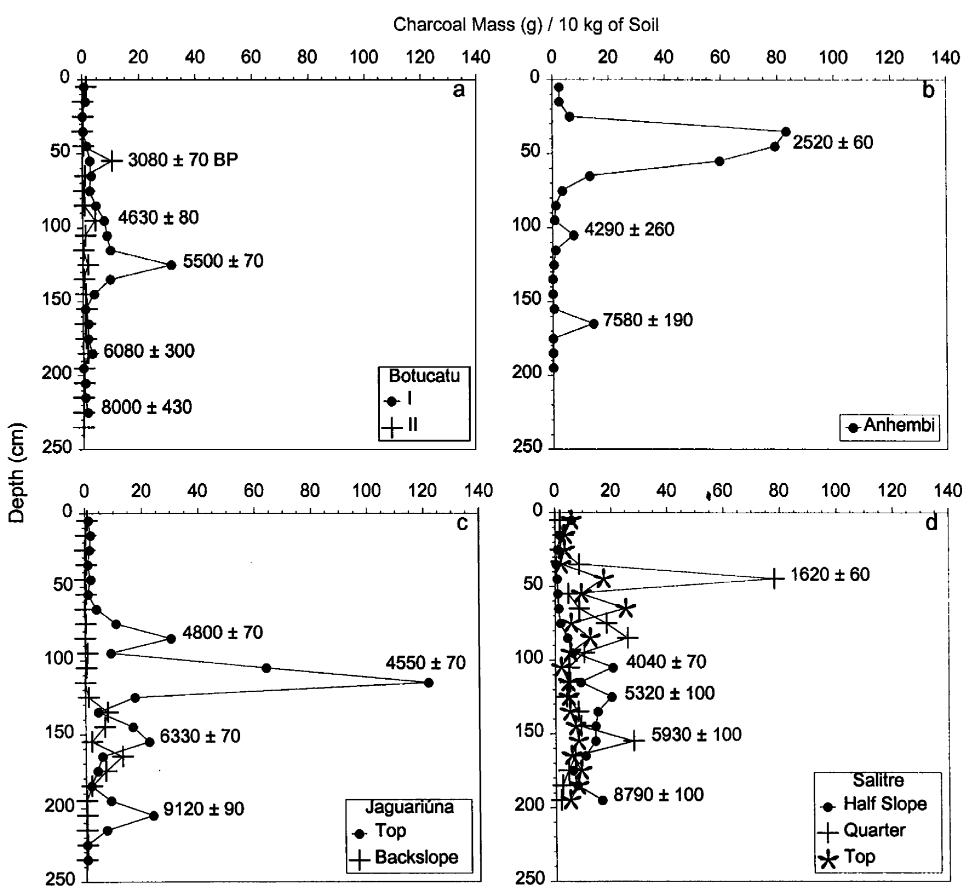

Fig. 4. Charcoal distribution as a function of soil depth and ^{14}C ages.

during the Holocene in the Amazon region (Absy, 1982; Van der Hammen, 1982; Sifeddine et al., 1994; Gouveia et al., 1997; Pessenda et al., 1998a, b; Freitas et al., 2001). Considering the general charcoal ^{14}C ages, they range from 1620 BP at 50 cm soil depth in Salitre (Fig. 4d) to 9120 BP at 2 m depth in Jaguariúna top (Fig. 4c).

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 and 6000 BP (Fig. 4a). Since the largest amount of charcoal (3.3 times) was found in soil profile I (about 1500 m distant from soil profile II), this could be related to the presence of denser arboreal vegetation and/or higher intensity and frequency of fire in Botucatu I than in II.

In the Anhembi area, the higher occurrence of fires was dated ca. 2500 BP (Fig. 4b). Considering that the age is relatively recent, these paleofires could probably be related to anthropogenic influence. In the north central Amazon Basin, evidence of human presence at 1400 and 3750 BP was described by Sanford et al. (1984). Smaller amounts of charcoal indicated the presence of fires at ca. 4300 and 7600 BP.

In the Jaguariúna soils, the highest abundance of charcoal was found in the top slope soil and dated between ca. 4000 and 9000 BP (Fig. 4c). In the backslope soil, charcoal fragments were not observed from the surface to 120 cm. This aspect can be related to the presence of Bt horizon (from 35 to 80 cm), which is marked by high shrink–swell, pulverizing charcoal during the burial mechanism (Gouveia and Pessenda, 2000). Considering that the profiles are separated by ~75 m, it is also possible 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. $\delta^{13}C$ values of SOM, discussed below, provide information to test the hypotheses about the presence of denser vegetation and or higher intensity of fire in Botucatu I and on the top of the slope in Jaguariúna.

In the Salitre soils the highest frequency of paleofires was observed in the period ca. 1620–8700 BP (Fig. 4d). Similar to Anhembi area, the more recent paleofires could probably be associated with anthropogenic influence.

Comparing the four sites, it can be seen that significantly larger amounts of charcoal were found in the Jaguariúna and Salitre regions. This aspect can be associated with the high frequency and intensity of paleofires, probably related to a climate variation (drier period) between ca. 6400 and 4000 BP. The presence of significant amounts of charcoal in the 150–210 cm soil interval in Botucatu (180–190 cm), Jaguariúna top (200–210 cm), Jaguariúna backslope, Anhembi (160–170 cm) and Salitre quarter (150–160 cm) could be indicative of a probable occurrence of paleofires during the Early- and Mid-Holocene. Based on charcoal ages, it is interesting to point out the consistent surface accumulation rates of soil matter of 0.24 mm yr^{-1} in Botucatu I, 0.27 mm yr^{-1} in Botucatu II, 0.23 mm yr^{-1} in Anhembi and Jaguariúna and 0.21–0.23 mm yr^{-1} in Salitre.

5. ^{13}C composition of SOM

^{13}C for SOM are shown in Fig. 5. The values between the surface and the 40–50 cm interval are representative of C_3 plants, reflecting the current local vegetation (forest) in all soil environments.

For Londrina and Piracicaba soils, the values show a significant change after the shallow interval, from −21.6‰ to −15‰, probably indicating a predominance of C_4 vegetation in both sites around the Early- to Mid-Holocene (Fig. 5a). The $\delta^{13}C$ value in the shallow part of the soil profile at Anhembi (−24.3‰) is characteristic of the modern vegetation cover, an open semideciduous forest (Fig. 5a). The values around −24‰ to −23.4‰ observed in the rest of soil profile indicate that the C_3-type vegetation has been predominant during the Holocene and probably Late Pleistocene at the study site.

No significant isotopic differences with depth are observed in the soil profile representing the Botucatu I site. The $\delta^{13}C$ values ranged from −26.3‰ in the surface to −24.7‰ at 210–220 cm (Fig. 5b). 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 (Boutton, 1991; Desjardins et al., 1996; Pessenda et al., 1996, 1998b). The $\delta^{13}C$ values suggest a predominance of C_3 plants during the Holocene at this site.

In the Botucatu II site (Fig. 5b), a significant enrichment of 3.9‰ was observed from the shallow soil horizon (−26.1‰) to 230–40 cm soil depth (−22.2‰). In addition to the SOM isotope fractionation, the presence of more open arboreal vegetation is the other possibility for ^{13}C enrichment. The relationship between native vegetation with higher/smaller arboreal densities and respective depleted/enriched $\delta^{13}C$ 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). This possibility of 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 BP, which was related with dry climatic conditions that probably occurred during the Early and Mid-Holocene. The presence of a significant amount of charcoal found in the soil of mid

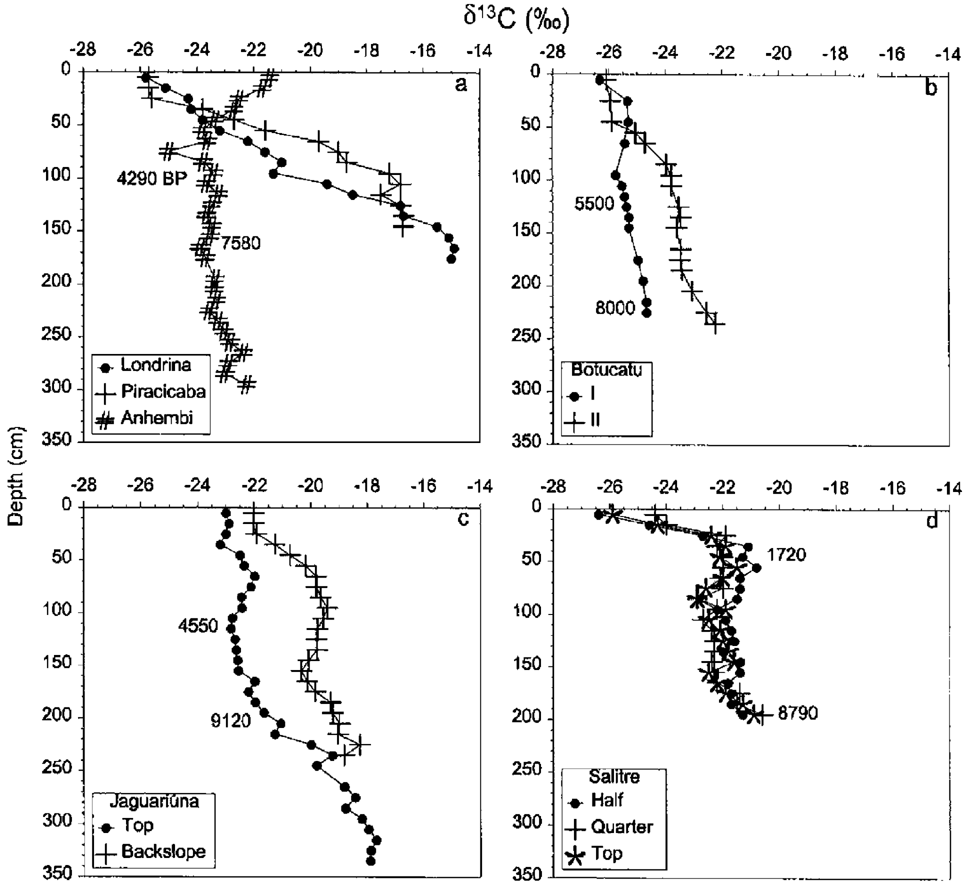

Fig. 5. $\delta^{13}C$ variation in relation to soil depth.

Holocene age (Fig. 4a) suggests high intensity and frequency of fires and also a probable drier climate.

As discussed earlier, the highest amount of charcoal encountered at Botucatu I site during the mid Holocene compared with Botucatu II site (Fig. 4a) suggests the presence of a larger density of trees in this site, in agreement with the information inferred from the $\delta^{13}C$ data. The soil isotopic data found in Botucatu region indicated the predominance of C_3 plants during the entire Holocene, suggesting that eventual drier climate in this region was not significant to change the vegetation ecosystem.

The $\delta^{13}C$ values obtained at the Jaguariúna sites (Fig. 5c) are clearly more enriched than in the other sites (Anhembi and Botucatu) from the São Paulo state. The soil profile collected on the top of the slope showed a $\delta^{13}C$ value of −23‰ in the surface, characterizing the vegetation cover, which 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 the Late Pleistocene.

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

The different pattern, more depleted $\delta^{13}C$ values at the Jaguariúna top 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 plants in the top site. This interpretation also agrees with the high amount of charcoal found at this site (Fig. 4c), suggesting a more significant presence of C_3 plants in 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 Late Pleistocene/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 period from ca. 9000 BP. In addition, the high amount of charcoal found in Jaguariúna may be related to a higher frequency and intensity of paleofires, supporting the existence of a drier climate.

For Salitre (Fig. 5d), the values range from −26.0‰ to −21.0‰ in the shallow part of the profile, and the isotopic trend observed could be due to isotope effect occurring during the decomposition of SOM (Becker-Heidmann and Scharpenseel, 1992) and/or a change from C_3 vegetation to a mixture of C_3 and C_4 plants. From ca. 8790–1720 BP, this mixture of plants was predominant in the study area.

In Central Brazil, in the Salitre area, Ledru (1993) based on pollen analyses observed changes during the last 32,000 BP. It was postulated that two major periods of forest retreat and the predominance of savanna vegetation (grasses) probably were associated with very dry climatic conditions between 11,000–10,000 and 6000–4500 BP. A dry period has also been reported in the Amazon Basin during the interval 8000–4000 BP (Sifeddine et al., 1994; Gouveia et al., 1997; Pessenda et al., 1998a, b; Freitas et al., 2001).

It seems that the dry phase (11,000–10,000 BP) registered by Ledru (1993) in the Salitre area, in connection with the isotopic soil data from Londrina, Paraná state and Piracicaba and Jaguariúna, São Paulo state, probably indicates that the subtropical region was much drier than the tropical region during climate changes in the Late Pleistocene/Early Holocene. Pollen records in the south, southeast, and central regions of Brazil also indicated the influence of a drier climate during a similar period (Behling, 1995a, b, 1997a, b; Ledru et al., 1998; Barberi et al., 2000).

The results obtained clearly show the complexities of vegetation response to eventual climate changes. They also show the need for the collection of multiple cores representing the different vegetation communities in the study regions, in order to infer a better understanding of past vegetation changes and their relation to climate changes.

6. Conclusions

Charcoal is present along the entire profile in most of the sampling locations. The presence of charcoal in these soils is a clear indication that the study areas in Botucatu, Anhembi, and mainly Jaguariúna and Salitre, have been affected by forest fires during the whole Holocene. The extremely high charcoal content in some soil horizons indicated that these events were much more severe during some periods, probably related with the presence of drier climatic conditions during the Early to Mid-Holocene. Enriched $\delta^{13}C$ values recorded at deeper to middle part of soil profiles suggested higher influence of C_4 plants in the majority of study sites during the Early to Mid-Holocene, supporting the presence of a drier climate, also observed in pollen records in the south, southeast, and central regions of Brazil. The collection of multiple cores representing the different vegetation communities in the study site, as well as the development of a multi/interdisciplinary study involving distinct techniques and matrices (carbon isotopes of SOM, pollen and geochemical analyses in sediments and peat, etc) will be certainly useful in order to infer better understanding of past vegetation changes and their relation to climate changes.

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