Holocene palaeoenvironmental evolution in the São Paulo State (Brazil), based on anthracology and soil $\delta^{13}C$ analysis

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Abstract: This paper presents a reconstruction of the Holocene palaeoenvironmental evolution in the central São Paulo State (Brazil) based on anthracological analyses, in association with soil isotopic composition ($\delta^{13}C$) and radiocarbon dating from four sites. Anatomical identification of charcoal particles allows the reconstitution of past plant associations, and consequently of the vegetation and climate history. Rather precise interpretations may be achieved when associating anthracology and soil $\delta^{13}C$ analysis. In the early Holocene, climate was dry and an open *cerrado* vegetation (savanna) covered most of this area. A *cerradão* (forested savanna) or a semideciduous forest existed in the more humid localities. After 3500/3000 ^{14}C yr BP the climate was more humid, similar to the present, leading to the establishment of forested vegetation in all the studied sites. Comparison of these results with various palaeoenvironmental studies carried out in the Brazilian phytogeographical zone of *cerrado* and semideciduous forest suggests that at least its greater part presented a similar trend in the climatic evolution during the Holocene. This phytogeographical zone presented a dry climate during the early Holocene, then a more humid climate during the late Holocene. Climatic conditions similar to the present appeared from 5000 to 1000 yr BP, depending on the site.

Key words: Palaeoenvironment, palaeoclimate, anthracology, charcoal, savanna, soil isotopic composition, oxygen isotopes, Brazil, Holocene.

Introduction

Charcoal fragments are frequent in Brazilian soils. They are present in the savannas of central Brazil, e.g., in São Paulo (Penteado, 1968; Coutinho, 1981; Scheel *et al.*, 1995; Melo *et al.*, 1996; Gouveia *et al.*, 1999) and Minas Gerais States (Vernet *et al.*, 1994; Pessenda *et al.*, 1998), but also in areas presently occupied by dense evergreen forests (Soubiès, 1980; Sanford *et al.*, 1985; Servant *et al.*, 1989). Many charcoal horizons dated from the late Pleistocene and the Holocene have also been found in Amazonian French Guyana (Tardy, 1998). These vestiges, mostly recording natural fires, are the result of dry periods and suggest the occurrence of climatic changes in the past.

Many palaeoenvironmental studies, mostly based on palynological analyses, have shown that important climatic oscillations affected the Brazilian territory during the late Quaternary (see, for example, Absy *et al.*, 1991; Oliveira, 1992; Ledru *et al.*, 1995; Ferraz-Vicentini and Salgado-Labouriau, 1996). The climate in different Brazilian regions seems to have evolved distinctly, since many of these oscillations were not synchronous, or divergent.

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For instance, the late Holocene is characterized by rising humidity in the Amazon region (Absy *et al.*, 1991) and in southern Brazil (Behling, 1996), both after *c.* 3000 yr BP, while in the northeastern *caatinga* there is a marked decline in moisture levels after *c.* 4000 yr BP (Oliveira *et al.*, 1999). A significant effort in new studies and the use of new techniques might improve our knowledge of the Brazilian palaeoenvironmental history and eventually improve our understanding of present and future climatic changes.

Microscopic charcoal found in soil or in lake sediments have long been used to reconstruct fire histories and to postulate climatic changes (Byrne *et al.*, 1977; Salgado-Labouriau and Ferraz-Vicentini, 1994; Piperno, 1997; Behling, 2000; Haberle and Ledru, 2001), but they cannot be used to reconstruct the vegetation history.

The occurrence of macroscopic charcoal (>0.5 mm) in soils provides solid evidence for local fire influence and can be used to identify fire-prone areas with high spatial precision (Ohlson and Tryterud, 2000). Anatomical identification of the charcoal particles (anthracological analysis) also allows the reconstitution of past plant associations, of the vegetation history, and consequently of palaeoclimate.

Identification of ancient charcoal is based in the analysis of the wood anatomy, which is very well preserved after carbonization. Taxonomic determination, frequently at genus level, is quite accurate. In the tropics, only charcoal pieces over 4 mm are usually analysed. Smaller fragments are normally impossible to identify, because in general they do not present a sufficiently large set of anatomical characters (Scheel-Ybert, 2001).

Anthracological work applied to soils is still rare, but some studies have already allowed reconstruction of the vegetation history for the late Pleistocene and the Holocene, e.g., in sites from Australia (Hopkins *et al.*, 1993), France (Carcaillet, 1998) and French Guyana (Tardy, 1998).

Study of the isotopic composition of soils also allows deduction of the plant cover in a site, since plants of different photosynthetic pathways have distinct carbon stable-isotope values. This analysis is based on the determination of $\delta^{13}C$ values of soil organic matter (SOM). $\delta^{13}C$ values of C_3 plants (shrubs and trees in general) vary between –32‰ and –20‰ PDB, while C_4 plants (grasses) range from –17‰ to –9‰ (Boutton, 1991). $\delta^{13}C$ analysis at different depths in soil profiles can characterize transitions between C_3- and C_4-dominated vegetation types. ^{14}C dating of charcoal samples characterizes the events chronology.

This study presents results on the Holocene climatic history in the São Paulo State, based on anthracological analysis, soil isotopic composition analysis and charcoal radiocarbon dating from four sites. It supports and completes the results already obtained by Gouveia *et al.* (1999; 2002), who presented palaeoenvironmental reconstruction and inferred climate changes during the late Pleistocene and the Holocene in southeastern and central-western Brazil, based principally on isotopic approaches, and Gouveia and Pessenda (2000), who studied the role of biological remount of soil matter and colluvium in the formation of ferrasols of São Paulo State.

Previous work

Palaeoenvironmental investigations are still rare in the São Paulo State. However, various palaeoecological studies exist for the same phytogeographical zone, specially in southern and central Brazil. They are summarized in Figure 1.

At Piracicaba (22°43′ S–47°38′ W), the analysis of SOM carbon isotopes showed more enriched $\delta^{13}C$ values (around –16‰) at the deeper part of the profiles and more depleted (around –26‰) at the upper part. These results suggest a dry period and the presence of grasses before *c.* 3500 yr BP, and an increasing in humidity thereafter (Pessenda *et al.*, 1998).

In São Paulo City, a dry climate has been identified around 4700 yr BP, characterized by high percentages of grass pollen in peat-bog samples from the Vale do Anhangabaú (Takiya and Ybert, 1991).

In Lago da Serra Negra (19°00′ S–46°50′ W) a dry phase, with *cerrado* vegetation, is identified from the early Holocene to 5000 yr BP, followed by a more humid climate and by the establishment of the semideciduous forest (Oliveira, 1992).

In Salitre (19°00′ S–46°46′ W), pollen analysis allowed the identification of two phases of increasing *cerrado* vegetation during the late Pleistocene and the Holocene: 11000–10000 and 5500–4500 yr BP. The later interval is characterized by the author as arid. Between 10000 and 8000 yr BP climate would be cold and humid and an *Araucaria* forest would be present on the site. Between 8000 and 5500, and after 4500 yr BP, the climate was warm and humid, similar to the present, with establishment of the semideciduous forest (Ledru, 1993). Quantification of charcoal in a soil profile from this same region indicated a more humid period, with decreasing of the fire frequency, only after *c.* 3000 yr BP (Vernet *et al.*, 1994). SOM carbon-isotope analysis and charcoal dating in three profiles suggested the existence of a mixture of trees and grasses from the early Holocene to *c.* 1700 yr BP. After this period until the present, the predominance of C_3 vegetation (forest) is attributed to an increasing of the humidity in the region (Pessenda *et al.*, 1996).

A dry period during the early Holocene is recognized also in Lagoa Santa (19°30′ S–44°07′ W). There, humidity increased after 5400 yr BP and a vegetation similar to the present (mosaic of *cerrado*, semideciduous forest and gallery forest) was established after *c.* 4600 yr BP (Parizzi *et al.*, 1998). In the same region, at Lagoa dos Olhos (19°38′ S–43°54′ W), a dry period with frequent fires between *c.* 13700 and 7000 yr BP, characterized by *cerradão* and *cerrado*, was followed by a phase of increasing humidity between 7000 and 4000 yr BP. After 4000 yr BP, the climate became even more humid and there was establishment of the semideciduous forest, which still coexisted with *cerrado* vegetation. Present climatic conditions were reached around 1300 yr BP (Oliveira, 1992).

At Lago do Pires (17°57′ S–42°13′ W), a dry climatic phase with *cerrado* vegetation is recorded between 9700 and 8800 yr BP; expansion of the gallery forests indicates a slightly more humid climate between 8800 and 7500 yr BP; then another dry climatic phase is recorded between 7500 and 5500 yr BP. After this time, the vegetation evolved to a *cerradão* which was maintained until 2700 yr BP, when a more humid climate allowed the establishment of a denser vegetation. Increasing humidity allowed the establishment of the semideciduous forest characteristic of this region at around 1000 yr BP (Behling, 1995).

Other authors identified significant climatic changes in South America during the late Quaternary (see, for example, Van der Hammen, 1991; Absy *et al.*, 1991; Servant *et al.*, 1993). Studies have suggested that in the north of the continent climate was colder and drier before 10000 yr BP; humid, similar to the present in the interval 10000–8000 yr BP; colder and drier at 6000–4000 yr BP, and similar to the present since 4000 yr BP (Markgraf and Bradbury, 1982). In central and southern Brazil (15–35° S) three major palaeoenvironmental phases are distinguished during the Holocene: dry climatic conditions between 10000 and 7000 yr BP, increasing moisture levels and a more seasonal climate between 7000 and 4000 yr BP, and establishment of modern conditions after 4000 yr BP, with development of the *cerrado* vegetation to the north, semideciduous forest in the centre and *Araucaria* forest to the south of the area considered (Ledru *et al.*, 1998). In the eastern Amazonia and in central Brazil frequent forest fires and an opening of the vegetation are noticed between

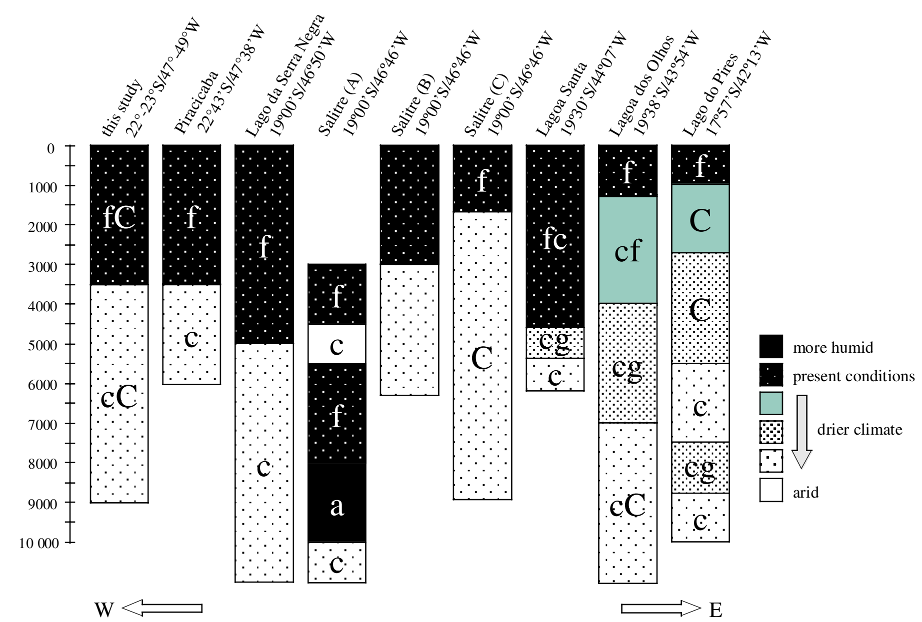

Figure 1 Summary of climatic changes documented for the *cerrado* and semideciduous forest phytogeographical zone in southern and central Brazil. São Paulo State: Piracicaba (Pessenda *et al.*, 1998); Minas Gerais State: Lago da Serra Negra (Oliveira, 1992); Salitre: A (Ledru, 1993); B (Vernet *et al.*, 1994); C (Pessenda *et al.*, 1996); Lagoa Santa (Parizzi *et al.*, 1998); Lagoa dos Olhos (Oliveira, 1992); Lago do Pires (Behling, 1995). c = *cerrado sensu amplo*; C = *cerradão*; f = semideciduous forest; g = gallery forest; a = *Araucaria* forest.

8000 and 4000 yr BP, indicating a dry climatic phase (Turcq *et al.*, 1996). After 4000 yr BP the climate was more humid, with forest reconstitution in many areas (Turcq *et al.*, 1996; Pessenda *et al.*, 2001; Freitas *et al.*, 2001).

Regional setting

In this study, samples from sites Botucatu (22°51′ S–48°29′ W), Jaguariuna (22°40′ S–47°10′ W), Anhembi (22°45′ S–47°58′ W) and Pirassununga (22°02′ S–47°30′ W), in the São Paulo State (Figure 2), were analysed for anthracology, soil isotopic composition ($\delta^{13}C$) and radiocarbon dating.

The study area is located in the southeastern part of the *cerrado* phytogeographical zone, at the transition to the semideciduous forest zone. Both vegetation types occur under a tropical seasonal climate. The average annual precipitation in most areas of this region ranges from 1000 to 1750 mm, the average annual temperature is 20–26 °C, and the dry season lasts 5–6 months in the *cerrado* and 3–5 months in the semideciduous forest (Nimer, 1989).

Semideciduous forests contain trees up to 30 m high with an important component of understorey vegetation. *Hymenaea*, *Copaifera*, *Peltophorum*, *Astronium* and *Aspidosperma* are some of the dominant genera in this formation (IBGE, 1992).

The *cerrado* (Brazilian savanna) is a vegetation type of low trees with twisted branches and stems, growing in the midst of herbaceous and dwarf woody plants. In fact, the *cerrado* is a vegetation gradient that includes five principal physiognomies (Coutinho, 1990). The *cerradão* is a forested formation with trees up to 15 m high, without a shrubby understorey but with a herbaceous stratum in tufts. Arboreal species such as *Curatella americana*, *Qualea grandiflora*, *Q. parviflora*, *Caryocar brasiliense*, *Bowdichia virgilioides* and *Stryphnodendron barbatiman* are typical of this formation. Although the *cerrado* has typical arboreal vegetation, the *cerradão* has a flora composition that is partially the same as the semideciduous forest (Leitão Filho, 1992). The *cerrado sensu stricto* is characterized by sparse trees and shrubs up to 5 m high. Its floristic composition is similar to the *cerradão*, but the trees are smaller and sparser, while the understorey vegetation of shrubs and grasses is more significant. Its most typical species are *Stryphnodendron adstringens* and *Dimorphandra mollis*. The *campo cerrado* and the *campo sujo* are intermediate savanna formations consisting of grassland with scattered rachitic woody plants, without an arboreal cover. Representative taxa are *Andira humilis*, *Byrsonima* spp. and species of Palmae, Compositae and Malvaceae. The *campo limpo* is basically a grassland.

At present, poor patches of secondary semideciduous forest, surrounded by agro-pastoral fields, exist in Botucatu, Jaguariuna and Anhembi. At Botucatu, the arboreal stratum is dominated by *Anadenanthera* cf. *macrocarpa* (Leguminosae), and at Anhembi by *Peschiera fuchsiaefolia* (Apocynaceae). In Jaguariuna, the very open forest is dominated by *Eucalyptus* exogenous species. *Bauhinia* and *Piptadenia* (Leguminosae) are also well represented. Present vegetation in Pirassununga is *campo-cerrado*. A gallery forest exists near the sampling site.

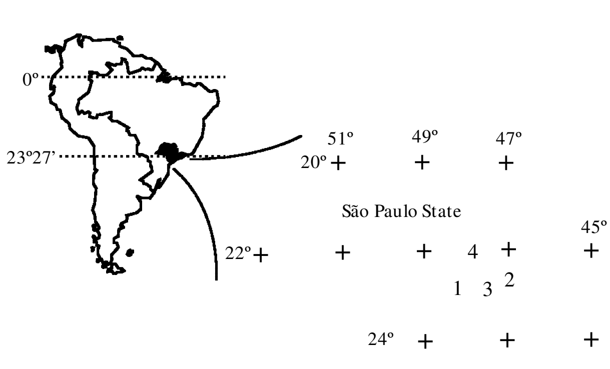

Figure 2 Study area in the São Paulo State, Brazil. (1) Botucatu; (2) Jaguariuna; (3) Anhembi; (4) Pirassununga.

Material and methods

Charcoal and soil samples from Botucatu (BOT and BOT II), Jaguariuna (JAG and JAG II) and Anhembi (PIN) were collected in trenches 1.0 m × 2.0 m large, up to 2.4 m in depth. Soils were sampled by collecting up to 10 kg of material in 10 cm layers. Samples deeper than 240 cm were drilled from the base of the trenches using an auger. Botucatu samples were taken in two trenches, at the top of two slopes *c.* 1500 m apart, at the Fazenda Experimental Lageado, Faculty of Agronomy Sciences, São Paulo State University (UNESP). In Jaguariuna, samples were collected from two trenches located at the top and middle parts of a slope separated by *c.* 75 m, at the Centro Nacional de Pesquisa de Monitoramento e Avaliação de Impacto Ambiental (Embrapa).

The sample from Pirassununga (EMAS) was collected from a single layer of *c.* 20 cm, between 180 and 200 cm depth from a trench 5 m long (Coutinho, 1981). Sampling was undertaken in an area of *Ferrovia Paulista*, along the road between Pirassununga and Cachoeira das Emas.

In the laboratory, soil samples from Botucatu, Jaguariuna and Anhembi were dried and sieved through a 2 mm mesh. $\delta^{13}C$ analysis was carried out at the Laboratory of Environmental Isotopes, University of Waterloo (Canada) and at the Laboratory of Stable Isotopes, Center for Nuclear Energy in Agriculture (Piracicaba, Brazil). Results are expressed relative to the international standard PDB. Precision for three determinations was ±0.2‰.

Charcoal fragments present in the soil were hand-collected. Large charcoal samples (>10 g) were subjected to acid-alkaline-acid treatments for removal of resins, fulvic acids and lignin. After drying, dating was carried out at the ^{14}C Laboratory of the Center for Nuclear Energy in Agriculture, using the benzene synthesis and liquid scintillation counting method (Pessenda and Camargo, 1991). Small charcoal samples (<2 g) were entirely combusted and CO_2 samples sent for AMS dating at the Isotrace Laboratory (Toronto, Canada). Results are representative of the mean charcoal age for each 10 cm layer.

The remaining fragments were examined for anthracological analysis under a reflected light microscope. Charcoal pieces were *c.* 1 cm of average size in all samples. Most of the charcoal was partially vitrified (fibre cells were 'melted', while parenchyma cells seemed normal). Systematic identification was carried out with the help of a program for computer-aided identification, coupled to a data bank of anatomical features from extant and fossil charcoal (Scheel-Ybert *et al.*, 1998), and by comparing the fossil material with a reference collection of charred wood and with descriptions and photographs from the literature (Gregory, 1994).

The results are presented as presence/absence of taxa. Cumulative histograms indicate the number of *cerrado* and forest taxa. Taxa that present species on both formations were classified as 'forest/*cerrado*'.

Results and interpretation

Most of the anthracological samples analysed at each site present only a small number of fragments and few taxa. Results must therefore be considered carefully.

In Botucatu, profile BOT covers the last 8000 years (Figure 3). It shows an important contribution of *cerradão* taxa in the lower levels – Vochysiaceae (*Qualea* sp., *Vochysia* sp.) are typical of the *cerrado*, but particularly frequent in the *cerradão* – and an increasing contribution of forest taxa (*Sebastiania* sp., *Cryptocaria* sp., *Acacia* sp.) in the upper levels (0–80 cm). Some forest taxa are also present between 140 and 190 cm (*c.* 6000 to 5500 yr BP).

Profile BOT II covers the last 6700 years (Figure 4). Typical forest taxa are present only in the lower levels (120–200 cm), from *c.* 6500 to 5700 yr BP, in a period when these taxa are also present in BOT. Open *cerrado* taxa are rare all along the profile, but *cerradão* elements are abundant between 40 and 170 cm depth

	Taxon	Forest				Forest / Cerrado			Cerrado					
¹⁴C age	*Level*	*Piptocarpha* aff. *macropoda*	*Sebastiania* sp	*Cryptocarya* sp	cf. *Acacia* / *Acacia* sp	Leguminosae spp	*Luehea* sp	Unidentified	*Peltogyne* sp	*Dimorphandra* sp	*Qualea* spp	*Vochysia* sp	cf. Vochysiaceae	*Number of charcoal pieces*
	0-10				*	*		*						9
	30-40				*	*	*							6
	40-50						*			*				12
	50-60		*					*						12
3040 ± 180*														
	70-80			*	*		*							12
4150 ± 110														
4630 ± 80														
4830 ± 70														
5500 ± 70	**120-130**										*		*	22
5560 ± 80														
	140-150	*									*		*	15
	150-160							*			*			14
	160-170							*			*	*		20
	170-180										*			16
6080 ± 300*	**180-190**				*									4
	200-210										*	*		10
	210-220					*						*		16
8000 ± 430*	**220-230**								*			*		5

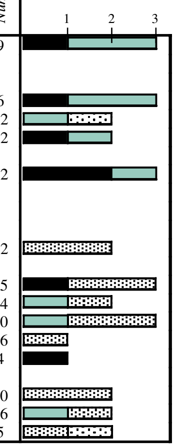

Figure 3 Botucatu (profile BOT). Results of anthracological analysis (presence of taxa in each sample) and number of charcoal pieces analysed per sample. Histograms indicate the number of taxa from each vegetation type (■ forest; ■ forest or *cerrado*; ▩ *cerradão* (arboreal savanna); ▩ *cerrado sensu amplo*). *AMS ^{14}C dates.

(*c.* 6000 to 3000 yr BP). 'Forest/*cerrado*' taxa are present in the majority of the samples. The most important, in the upper levels, are *Croton* and *Luehea*, genera that have several species typical of semideciduous and gallery forests.

Anthracological results from both sites point to the existence of forested vegetation in Botucatu during all the studied period, with an important contribution of semideciduous forest and *cerradão* taxa.

Soil organic matter $\delta^{13}C$ analysis (Figure 5) complements this approach. In BOT, $\delta^{13}C$ values vary between –24.7‰ (210–220 cm) and –26.3‰ (surface level), indicating arboreal vegetation through the entire profile. In BOT II, $\delta^{13}C$ values fluctuate from –22.3‰ (lower levels) to –26.1‰ (surface). This indicates the predominance of arboreal C_3 vegetation. In the lower levels, ^{13}C enrichment may be explained by the SOM isotope fractionation (Nadelhoffer and Fry, 1988; Boutton, 1991), but the existence of a more open arboreal vegetation and a greater influence of C_4 plants (grasses) is also possible.

In Jaguariuna, there are chronological inversions in the two studied profiles. In JAG, these inversions are attributed to bioturbation (Gouveia *et al.*, 1999; Gouveia and Pessenda, 2000; Gouveia, 2001). There are three series of ages relatively similar (Figure 6), delineating different sedimentary blocks. In JAG II, besides the biological activity, the inversions are attributed to the colluvial nature of the deposit (Gouveia *et al.*, 1999; Gouveia and Pessenda, 2000; Gouveia, 2001). Indeed, there is in JAG (situated upstream) a possible sedimentary hiatus between 180 and 200 cm, since the date 6240 yr BP (level 170–180 cm), is followed by 9120 yr BP (level 200–210 cm). This material is found in JAG II (situated downstream) between 120 and 240 cm, where several dates cluster around 8000 yr BP. We assume this material can be used for palaeoenvironmental reconstruction, because colluvial source is very near and, in consequence, charcoal pieces reflect the local vegetation. In both cases (JAG and JAG II), $\delta^{13}C$ curves present a characteristic zigzag trend which suggests that soil material was reworked (Schwartz, personal communication). However, chronological inversions do not invalidate the palaeoenvironmental interpretations proposed, because the general

Habitat		Forest			Forest / Cerrado								Cerrado					
^{14}C age	Level (Taxon)	*Sebastiania* sp	*Cryptocarya* sp	cf. *Acacia* / *Acacia* sp	*Croton* sp	*Anadenanthera* sp	Leguminosae	cf. Leguminosae/Vochysiaceae	*Guettarda* sp	*Luehea* sp	Palmae	Unidentified	*Peltogyne* sp	*Qualea* sp	*Vochysia* sp	cf. Vochysiaceae	Gramineae	*Number of charcoal pieces*
	0-10										*						*	8
	40-50				*				*	*					*			5
3080 ± 70*	50-60											*						2
	60-70									*								6
	70-80													*				5
	80-90				*					*				*				8
4630 ± 80*																		
	100-110				*										*			10
	110-120												*	*	*	*		8
5660 ± 270*	120-130			*			*											8
	130-140			*			*											5
	140-150														*			6
	150-160	*		*			*											9
	160-170												*		*	*		18
	170-180		*			*		*										5
	190-200		*			*												7
	200-210											*						4
6690 70*																		

Figure 4 Botucatu (profile BOT II). Results in anthracological analysis (presence of taxa in each sample) and number of charcoal pieces analysed per sample. Histograms indicate the number of taxa from each vegetation type (see legend for Figure 3). *AMS ^{14}C dates.

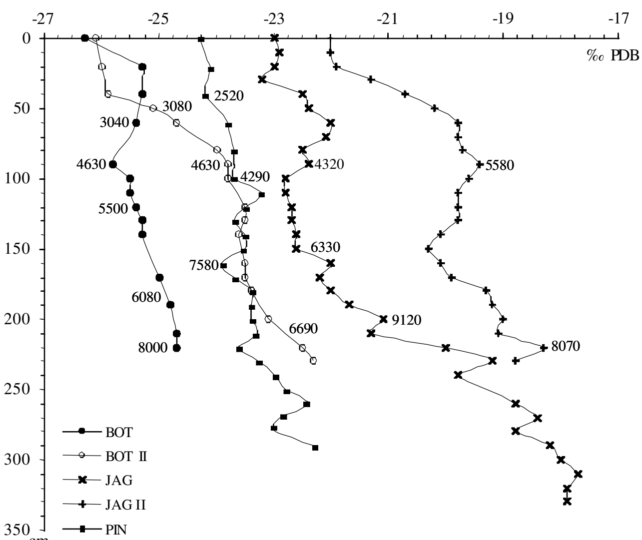

Figure 5 Soil organic matter δ^{13} C variation (in % PDB) in Botucatu (BOT and BOT II), Jaguariuna (JAG and JAG II) and Anhembi (PIN) as function of soil depth. ^{14}C ages are given for each curve.

trends of climatic evolution may be inferred from the different sedimentary blocks, among which the chronological sequence is coherent.

In the JAG profile, anthracological results cover the last 9000 years (Figure 6). Typical forest taxa are restricted to the upper part of the profile (0–30 cm), probably after *c.* 3000 yr BP. Taxa typical of the *cerrado* (*Andira*, *Bowdichia*, *Qualea*, etc.) are abundant in the lower levels (80–260 cm). 'Forest/*cerrado*' taxa (e.g., *Tabebuia* sp., *Cassia* sp., Leguminosae) are present throughout the profile.

JAG II profile covers the last 8000 years (Figure 7). Forest taxa are also restricted to the upper levels (0–40 cm), probably after *c.* 3000 yr BP. Between 50 and 120 cm 'forest/*cerrado*' taxa predominate (various Leguminosae species), while in lower levels (150–240 cm), around 8000 yr BP, there is practically a single species (cf. *Andira*), typical of the *cerrado.*

These results suggest the presence of *cerrado* on this site during the late and mid-Holocene, and the establishment of a forested vegetation after *c.* 3000 yr BP.

The $\delta^{13}C$ analysis of soil samples (Figure 5) shows in both profiles the predominance of forested formations after *c.* 3000 yr BP, with values between –23.0‰ and –20.7‰. Both curves show higher $\delta^{13}C$ values between *c.* 3000 and 5500 yr BP, slightly decreasing values from *c.* 5500 to 6500 yr BP, then increasing values from *c.* 6500 yr BP to the base. The lower levels present $\delta^{13}C$ values characteristic of a vegetation type where C_3 and C_4 plants coexist (–20‰ to –17.9‰), i.e., an open *cerrado* with a great proportion of grasses. In both profiles, higher $\delta^{13}C$ values in levels lower than 200 cm depth suggest the predominance of C_4 plants (grasses), i.e., probably a *campo-sujo*, prior to 8000 yr BP.

At Anhembi, anthracological results of the PIN profile cover the last 8000 years (Figure 8). The presence of *Securinega* aff. *guarayuva* in the surface sample indicates the existence of a forested formation in a recent period. The Gramineae charcoal in the same sample suggests it can be a *cerradão*. *Bauhinia* sp. is frequent in the upper part of the profile. Although it can occur in the open *cerrado*, this genus is mostly characteristic of a forested vegetation. *Dimorphandra* sp., typical of the *cerrado*, and *Qualea* sp., particularly frequent in the *cerradão*, occur in the lower part of the profile, from 80 cm to the base.

These results point out to the existence of an arboreal vegetation, possibly a *cerradão*, from the base of the anthracological sequence until *c.* 3000 yr BP, when the establishment of a dense *cerradão* or a forest occurred.

SOM $\delta^{13}C$ analysis also indicates the predominance of C_3 plants in the whole period (Figure 5). In lower levels (250–300cm), SOM $\delta^{13}C$ values are more enriched (–22.3‰ up to –23.0‰). In addition to the SOM fractionation, these enriched values can be related to the existence of a more open arboreal vegetation and to the influence of C_4 plants at the early Holocene, probably due to the presence of a drier climate. From 240 cm to the soil surface, and particularly in the upper 50 cm (after 3000 yr BP), $\delta^{13}C$ values are more depleted (up to –24.3‰), suggesting the progressive establishment of a forested formation, probably related to a more humid climate.

The Pirassununga sample (EMAS) shows a clear predominance of *Acosmium* sp. and *Bowdichia* sp., typical of the *cerrado* (Figure

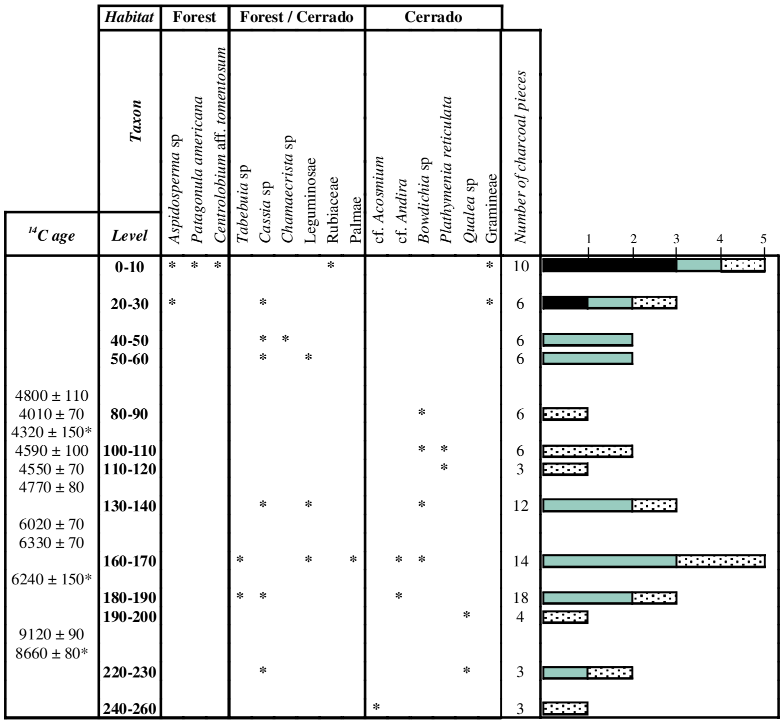

Figure 6 Jaguariuna (profile JAG). Results of anthracological analysis (presence of taxa in each sample) and number of charcoal pieces analysed per sample. Histograms indicate the number of taxa from each vegetation type (see legend for Figure 3). *AMS ^{14}C dates.

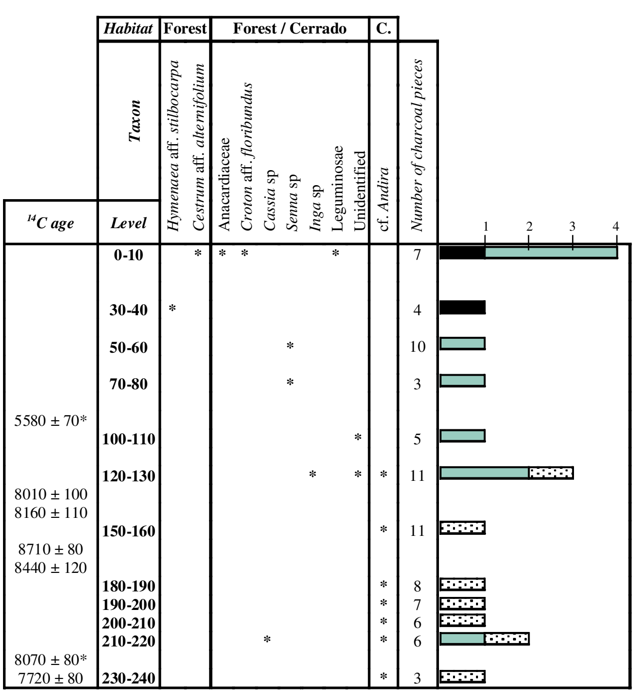

Figure 7 Jaguariuna (profile JAG II). Results of anthracological analysis (presence of taxa in each sample) and number of charcoal pieces analysed per sample. Histograms indicate the number of taxa from each vegetation type (see legend for Figure 3). *AMS ^{14}C dates.

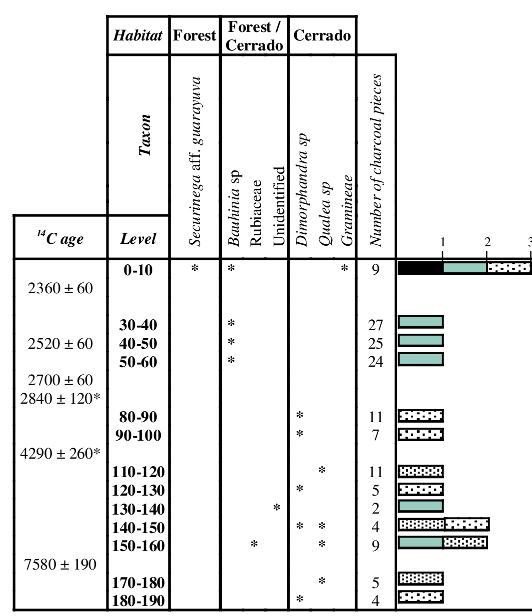

Figure 8 Anhembi (profile PIN). Results of anthracological analysis (presence of taxa in each sample) and number of charcoal pieces analysed per sample. Histograms indicate the number of taxa from each vegetation type (see legend for Figure 3). *AMS ^{14}C dates.

9), indicating that this vegetation was present in this site around 8600 yr BP. Soil δ^{13}C analysis was not carried out in this location.

Discussion

Reliable reconstitution of the local palaeovegetation based on anthracological studies would need a much larger sample size. A great number of charcoal fragments, ideally from a great number of trenches widely distributed over each site, might allow a very good reconstruction of floristic diversity and of plant cover evolution in the region. Indeed, as the charcoal fragments preserved in a site come from a limited number of trees burnt *in situ*, soil samples generally contain charcoal from a small number of species.

Despite these problems, charcoal identification provides important information on the local flora, particularly interesting as charcoal does not usually suffer significant transport and allows the inference of contemporaneous vegetation in the place of deposition.

Data suggest the existence of a vegetation shift, probably of climatic origin, in the late Holocene. Although δ^{13}C record of the

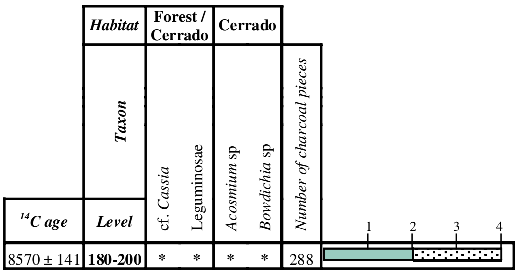

Figure 9 Pirassununga (EMAS). Results of anthracological analysis (presence of taxa) and number of charcoal pieces analysed. Histograms indicate the number of taxa from each vegetation type (see legend for Figure 3).

BOT site is distinguished from the other ones by a continuous forested vegetation, BOT II, JAG, JAG II and PIN profiles show a more open environment, possibly indicative of a drier climate, in the early Holocene, and a clear trend for a more forested environment, suggesting a more humid climate, during the late Holocene.

In Botucatu, anthracological and isotopic data indicate a vegetation of semideciduous forest or *cerradão* during the last 8000 years, denser in BOT than in BOT II. Isotopic data suggest that the BOT II site was probably covered by a *cerradão* with a more important herbaceous stratum before *c*. 3500 yr BP.

In Jaguariuna, anthracological results indicate that *cerrado* taxa are dominant before 8000 yr BP, suggesting a dry climate. Around 6500/6000 yr BP the 'forest/*cerrado*' taxa are more important, possibly suggesting a closer vegetation and a more humid climate. After *c*. 3000 yr BP climate is still more humid and the vegetation is probably a *cerradão*. $\delta^{13}C$ analysis of soil samples supports this interpretation.

At Anhembi, climate was probably drier before 8000 yr BP and slightly more humid from 7500 to 3000 yr BP, but during all this period the site was covered by a forested vegetation, probably of *cerradão* type. A still more humid climate become established after *c*. 3000 yr BP, when a dense *cerradão* or a forest covered the site.

SOM $\delta^{13}C$ and anthracological data point to a denser arboreal vegetation in Botucatu than in Jaguariuna over the entire period represented by the samples, as it is in the present days. Anhembi region experienced intermediate climatic conditions.

The evidence of an open environment at Jaguariuna throughout the Holocene is taken to be indicative of drier climatic conditions. This interpretation is further supported by a greater amount of charcoal in the soil than at Botucatu (Figure 10), which is probably related to a higher frequency and intensity of fires in this region (Gouveia *et al.*, 1999; Gouveia, 2001). Charcoal amounts are small in Anhembi (Figure 10), except between 30 and 50 cm depth, where the increase of charcoal in the soil is probably related to an important fire event around 2500 yr BP.

These data also have wider implications and testify to the antiquity of the *cerrado* ecosystem, and its ancient association with fire. At present, fire is an important factor in the *cerrado* ecosystem. The flora of the open *cerrado*, and especially that of the herbaceous/undershrub stratum, is typically pyrophytic. A great number of species are fire tolerant, showing that this ecological agent is ancient and important (Coutinho, 1990).

The existence of large *cerrado* areas is presently attributed to edaphic characteristics or to fire incidence (Queiroz Neto, 1982; Coutinho, 1990), but human action is considered primarily responsible (Coutinho, 1982). However, wildfire incidence since the late Pleistocene is now well established, even in much more humid environments such as the Amazonian Forest (Soubiès, 1980; Tardy, 1998; Freitas *et al.*, 2001). In *cerrado* areas, the occurrence of fire seems to have been a common event since before 32 400 until after 3500 yr BP (Salgado-Labouriau and Ferraz-Vicentini, 1994).

A more humid phase in central Brazil during the late Holocene, with development of the forests and establishment of climatic conditions similar to the present, is recognized by various authors (Oliveira, 1992; Ledru, 1993; Vernet *et al.*, 1994; Behling, 1995; Pessenda *et al.*, 1996; 1998; Parizzi *et al.*, 1998). There is broad agreement with the results of the present work (Figure 1). However, the humid periods proposed by Ledru (1993) between 10000 and 5500, as well as the arid phase around 5000 yr BP, seem highly improbable. All other studies carried out in this region show a drier climate during the early Holocene (Oliveira, 1992; Behling, 1995; Pessenda *et al.*, 1996; Parizzi *et al.*, 1998), but there is no moment in the climatic history of the last 40000 years of this region that can be described as arid (Oliveira, 1992).

Conclusion

This work has pointed out to the antiquity of the *cerrado* ecosystem in central-southern Brazil and its ancient association with fire. Charcoal fragments present in the soil attest that burning of the vegetation in this region occurred as early as 32 000 yr BP (Salgado-Labouriau and Ferraz-Vicentini, 1994), long before any known human activity. Anthracological analysis from four sites of the central São Paulo State, associated with soil organic matter $\delta^{13}C$ analysis and charcoal radiocarbon dating, has allowed the characterization of the Holocene palaeoenvironmental and palaeoclimatic evolution trend in this region.

In the early Holocene, an open *cerrado* vegetation probably existed at Jaguariuna; a *cerrado* (*sensu amplo*) at Pirassununga; an open *cerradão* at Anhembi; and an open semideciduous forest or a *cerradão* at Botucatu. These results are taken to suggest a dry climate with more humid conditions in the Botucatu region.

More humid conditions have progressively taken place. After 3500/3000 yr BP there was establishment of a *cerradão* at Jaguariuna, and of a denser *cerradão* or a semideciduous forest at Botucatu and Anhembi. This change is thought to be reflecting increasing humidity and the development of a climate similar to the present.

Comparison of these results with previous studies shows, in spite of local discrepancies, a great coherence in the palaeoenvironmental evolution trend of the phytogeographical zone characterized by the *cerrado* and the semideciduous forest of the central-southern region of Brazil. A dry climatic period is recorded during the early Holocene, followed by a more humid climate, similar to the present. Climatic conditions similar to the present appear from 5000 to 1000 yr BP, depending on the site. Palaeoenvironmental data obtained in four sites of the São Paulo State agree with this evolution, showing that the present climatic conditions appeared, in this region, around 3500/3000 yr BP. This suggests that at least the greater part of the *cerrado*/semideciduous forest phytogeographical zone presented a similar trend in the climatic evolution during the Holocene.

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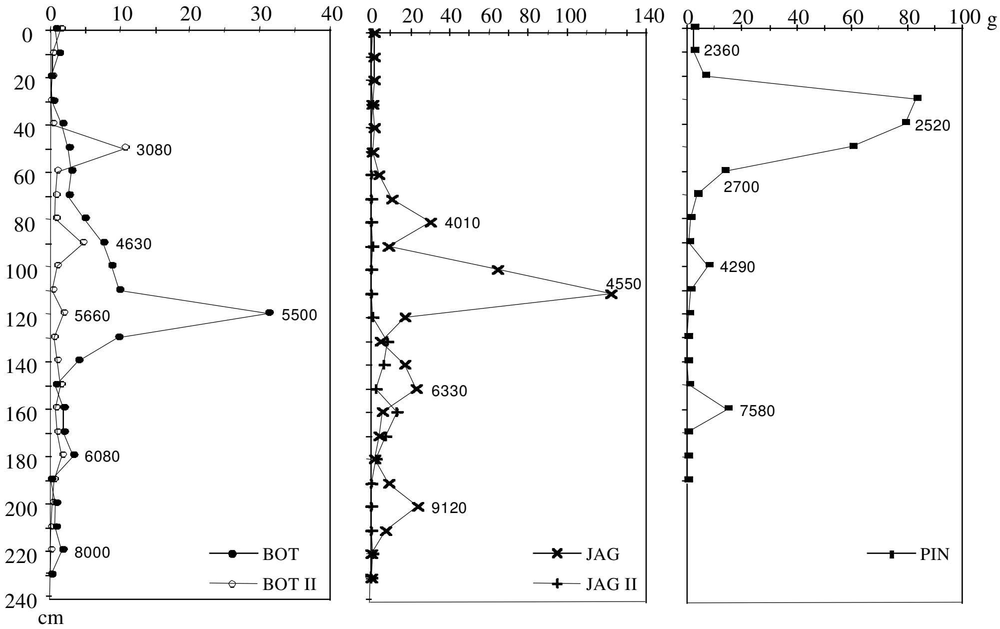

Figure 10 Distribution of charcoal in the soil at Botucatu (BOT and BOT II), Jaguariuna (JAG and JAG II) and Anhemi (PIN), as function of soil depth (in centimetres). X-axis presents the amount of charcoal, in grams, per 10 kg of soil (after Gouveia *et al*., 1999). ^{14}C ages are given for each curve.

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