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Last glacial maximum (LGM) vegetation changes in the Atlantic Forest, southeastern Brazil

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Abstract

This study was carried out in a continental Atlantic Forest located in the southern region of São Paulo State, southeastern Brazil. The aim of the study was to evaluate the vegetation dynamics in ~70 km forest ecosystem transect that occurred during the late Pleistocene and Holocene in this region, using the stable carbon isotopes ($\delta^{13}C$) analysis on soil organic matter (SOM) and the ^{14}C dating of buried charcoal fragments and the humin fraction of SOM. The isotope data ($\delta^{13}C$) of SOM in the deeper horizons, indicating the presence of more open vegetation than the present, with a probable mixture of C_3 and C_4 plants, suggesting the presence of a drier climate in the period of ~20 ka to ~16–14 ka BP. From ~16 to 14 ka BP to the present, a significant predominance of C_3 plants was observed, indicating an expansion of the forest, probably associated with the presence of a more humid climate than the previous period. The results indicated the presence of open vegetation during the late glacial, probably associated with a drier period, also observed in other regions of Brazil. The Atlantic Forest ecosystem seems to have developed at least since the early Holocene in southeastern Brazil.

Keywords: Late Pleistocene; Holocene; Soil organic matter; ^{14}C dating

1. Introduction

The Brazilian Atlantic Forest was considered the largest coastal forest in the world. At present, due to anthropogenic activities, is now reduced to only 7% of its original size (SOS Mata Atlântica, 2006). In the past, this type of forest covered ca. of 1,360,000 km^2 of the Brazilian coast, from Rio Grande do Norte State, northeastern, to Rio Grande do Sul State, southern (Avaliação, 2000).

In the south region of São Paulo State, southeastern Brazil, more specifically at Parque Estadual Turístico do Alto Ribeira (PETAR) and Parque Estadual Intervales (PEI), a very dense arboreal fragment of a continental part of a native Atlantic Forest still exists. The natural composition of this forest and the presence of relatively deep soils in the region, are favorable for the application of carbon isotopes (^{12}C, ^{13}C and ^{14}C) of soil organic matter (SOM), with the objective of studying the vegetation and related climate changes that occurred in the past in the region.

Up to date, no other palaeoenvironmental research has been developed in the Atlantic Forest fragments covering an area of ~70 km of extension of native vegetation. Some of the key questions concerning the effect of climate in the Atlantic Forest vegetation can include: what was the influence of the cold and dry climate on the vegetation dynamic of the forest ecosystem during the late glacial? Is it possible to find an opening of vegetation in the past, indicating a significant influence of the climate and the existence of a woody savanna and/or savanna communities, and the consequent presence of C_4 grasses in some areas in this region?

Carbon isotopes techniques in soil organic matter (SOM) have been applied to reconstruct palaeovegetation changes in south (Pessenda et al., 1996a), southeastern (Pessenda et al., 1996b, 2004a; Gouveia et al., 2002), central (Pessenda et al., 1996b; Gouveia et al., 2002),

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northern (Desjardins et al., 1996; Gouveia et al., 1997; Pessenda et al., 1998a, b, 2001a), and northeastern region of Brazil (Pessenda et al., 2001a, 2004a, b).

In this paper we report $\delta^{13}C$ data of soil and ^{14}C dates on humin fraction and charcoal fragments from four soil profiles collected at PETAR and three soil profiles collected at PEI, in order to evaluate eventual vegetation changes, with climate inferences, that occurred during the late Pleistocene (since ~20 ka BP) and Holocene in the region.

2. Study sites

Soil samples under natural vegetation (Atlantic Forest) were collected in PETAR at Iporanga (IPO), Morro do Tatu (IPO-Tatu), Bairro Camargo Baixo (CAMB), Bairro Lajeado (LDO) and in PEI at Base do Carmo (BCR), Bulha D'Água (BDA) and Saibadela (SAI), southern São Paulo State. The soils at PETAR are Dystrudept and at PEI Hapludox (American Soil Taxonomy—USDA classification) and considered well developed and relatively deep soils. The soil samples were collected from trenches or with hand auger, from location on the top of the slopes or closer as possible of the top (Fig. 1, Table 1).

The PETAR has an area of 35.884 ha and it is situated between the latitudes 24°20′–24°50′S and longitudes 48°30′–48°60′W. PEI has an area of 41,705 ha, located between 24°12′–24°32′S and 48°03′–48°32′W. The mean annual temperature is around 20–22 °C and mean annual precipitation is in the range of 1200–1800 mm. The regional climate is subtropical (Karmann, 1994; São Paulo (Estado), 1998, 2001). The distance between the two extreme sampling points in the ecosystem transect is about 70 km (Fig. 1).

The dominant arboreal plants are represented by the following families: Cyathaceae (*Cyat*heae sp), Euphorbiaceae (*Alchornea triplinervia* Muell. Arg.), Flacourtiaceae

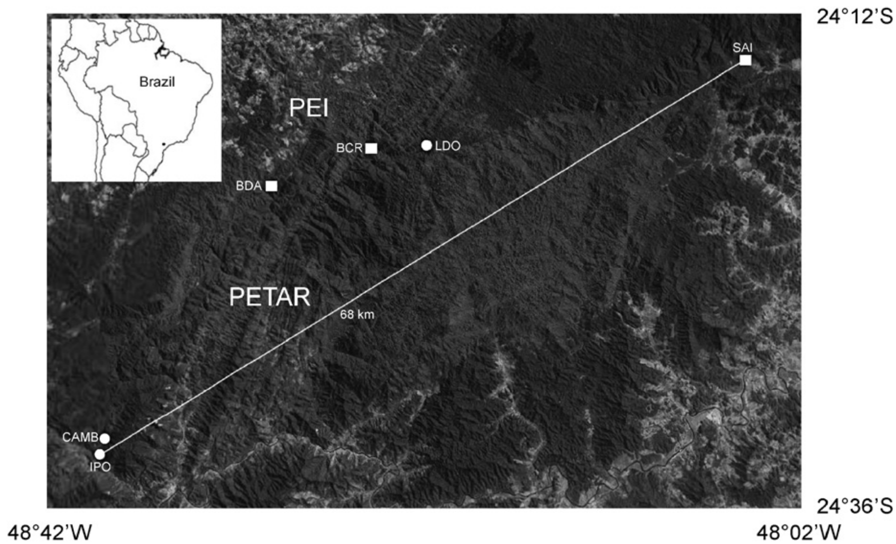

Fig. 1. Sampling points IPO, CAMB and LDO located at Parque Estadual Turístico do Alto do Ribeira (PETAR—●) and BDA, BCR and SAI located at Parque Estadual Intervales (PEI—■).

Table 1
Vegetation cover, altitude and soil sampling type in the locations of PETAR and PEI

Study site		Vegetation	Location	Altitude (m)	Sampling type
PETAR	IPO	Grass (anthropogenic)	24°33′19,0″S 48°39′27,4″W	300	Drilling
	IPO-Tatu	Forest	–	–	Drilling
	CAMB	Forest	24°32′31,5″S 48°39′11,5″W	735	Trench
	LDO	Forest	24°18′18,2″S 48°21′54,2″W	847	Trench
PEI	BCR	Forest	24°18′25″S 48°24′52″W	529	Trench
	BDA	Forest	24°20′15″S 48°30′09″W	592	Drilling
	SAI	Forest	24°14′25″S 48°48′52″W	100	Trench

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(*Casearia* sp), Melastomataceae (*Tibouchina pulchara* Cogn), Meliaceae (*Cedrela fissilis* Vell., *Guarea macrophylla* Vahl), Moraceae (*Ficus insipida* Willd., *Maclura trinctoria* (l.) D.Don. ex Steud.), Myrtaceae, Sapindaceae (*Cupania oblongifolia* Mart.). It was also observed the presence of Bromeliaceae and in a limited area one species of C_4 grass, that was probably introduced by humans.

3. Materials and methods

Soil samples were collected up to 400 cm depth for isotope analysis ($\delta^{13}C$) and ^{14}C dating of the buried charcoal fragments and humin fraction of SOM. Sampling in trenches involved the collection of up to 5 kg of material at 10 cm intervals. Samples were dried at 60 °C to constant weight and sieved (210 μm). Any remaining plant debris was removed by flotation in HCl 0.01 M. The humin fraction was extracted from the total soil from BCR and SAI sites using acid–alkaline–acid treatment (Pessenda et al., 1996b).

Buried charcoal fragments were collected by hand-picking from soil samples from LDO site and submitted to the conventional acid–alkaline–acid treatment (Pessenda and Camargo, 1991) and dried to a constant weight.

$\delta^{13}C$ analysis and the determination of carbon contents in soil samples were carried out at the Stable Isotopes Laboratory of Centro de Energia Nuclear na Agricultura (CENA), and at the Environmental Isotopes Laboratory, University of Waterloo, Ontario, Canada. Organic carbon results are expressed as percentage of dry weight. $\delta^{13}C$ results are expressed with respect to PDB standard using the conventional δ (‰ per mil) notations:

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

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

The ^{14}C analyses of charcoal fragments and humin fraction were carried out at the IsoTrace Laboratory of the University of Toronto (Canada) by AMS technique. Radiocarbon ages are expressed as ^{14}C yr BP (Before Present) normalized to a $\delta^{13}C$ of −25‰ PDB and in cal BP, using 2σ confidence limit (Stuiver et al., 1998). In the text it will be used only the results in yr BP.

4. Results and discussion

4.1. Soil organic carbon content

The total organic carbon (TOC) of PETAR and PEI soils are presented in Fig. 2. The shallow soil horizons presented values from 0.38% to 2.50%. In the LDO soil profile the higher value was observed in the shallow horizon (6.79%), probably related to the presence of more dense forest (higher biomass input) at this sampling point. In all profiles, the TOC decreases with depth reaching values as low as 0.03% at the deepest sampling intervals. Similar tendency was observed at other study sites of São Paulo State (Pessenda et al., 1996b) and Amazonas (Desjardins et al., 1996; Gomes, 1995; Pessenda et al., 1998a, b).

4.2. ^{14}C dating of charcoal fragments and humin fraction

The ^{14}C data of buried charcoal fragments from soil of LDO site are reported in Table 2 and Fig. 3. The radiocarbon dating results showed older ages with the increase of soil depth. For the 110–120 cm interval it was

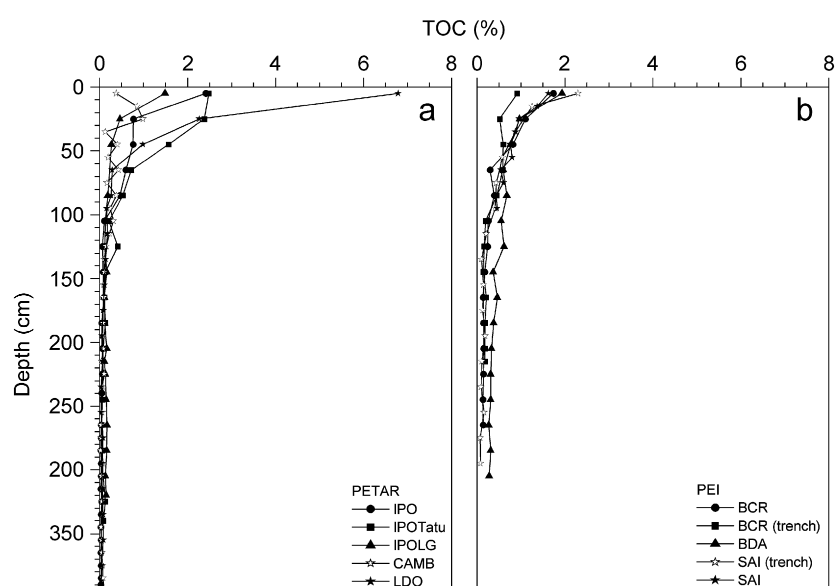

Fig. 2. Total organic carbon content of the PETAR and PEI soils in relation to the depth.

obtained a value of ~10.3 ka BP, for 130–140 cm ~14.4 and ~16.2 ka BP for 140–150 cm. The radiocarbon dates indicated older ages (up to ~100%) in relation to charcoal fragments dated in others sites of Brazil in similar depths (Pessenda et al., 1996a, 1998a, 2001b, 2005; Gouveia et al., 2002).

The results of the ^{14}C dating of the humin fraction of PEI soils (SAI and BCR sites) are reported in Table 2 and Fig. 4. The humin ages at SAI site show the typical profile of increasing age with soil depth in agreement with other studies (Balesdent, 1987; Balesdent and Guillet, 1992; Becker-Heidmann et al., 1988; Pessenda et al., 1996b, 1998b, 2001b; Gouveia and Pessenda, 2000; Gouveia et al., 2002).

The ^{14}C dates of 13.8 ka BP for the 290–300 cm interval at SAI site and of 11.4 ka BP at 210–220 cm at BCR site are in agreement with other dates obtained in similar depth, in distinct sites of Brazil (Gouveia et al., 1997; Freitas et al., 2001; Mofatto, 2005; Vidotto et al., 2007). For the 90–100 cm soil interval at SAI site the age of 12.5 ka BP is older than ^{14}C dates routinely observed in soils of other study sites in Brazil, which present ages of ~4–6 ka BP for the same soil layer (Pessenda et al., 1996a, b, 1998a, b, c, 2001a, 2004a; Gouveia et al., 1997, 1999; Gouveia and Pessenda, 2000; Freitas et al., 2001).

As observed previously, the buried charcoal fragments at LDO site were also significantly older in similar soil layers, indicating that for these samples the surface accumulation rate of ~0.08–0.013 mm/yr was much lower than the 0.20–0.22 mm/yr obtained in Hapludox in other study sites in Brazil (Boulet et al., 1995). These results indicate that the low porosity, the high density and large aggregates of the Dystrudept soil found in the LDO site, probably had significant influence in the activity of soil fauna on the burial of charcoal fragments, as well as for the burial of the humin fraction in the layer 90–100 cm at the SAI site. The contribution of the characteristic soil genesis and specific colluvial process (Boulet et al., 1995; Pessenda et al., 2001a) of the whole soil profile or specific soil layer in the study of radiocarbon dating of buried charcoal fragments and humin fraction, cannot also be discarded.

Table 2
Radiocarbon dating of charcoal fragments collected in the LDO site and of humin fraction from SAI and BCR sites

Study site		Depth (cm)	Laboratory number	Age (yr BP)	Age (cal BP)
PETAR	LDO	110–120	TO-11914	10,300±90	11,750–12,400
		130–140	TO-11916	14,410±110	16,780–17,830
		140–150	TO-11917	16,210±120	19,050–19,560
PEI	SAI	90–100	TO-12424	12,480±110	14,140–15,010
		290–300	TO-12425	13,790±130	15,970–16,920
	BCR	210–220	TO-12426	11,390±100	13,080–13,440

TO-Isotrace laboratory, Toronto, Canada.

4.3. $\delta^{13}C$ of SOM

For the interpretation of the SOM $\delta^{13}C$ profiles, we assume that variations smaller than 4‰ are associated with

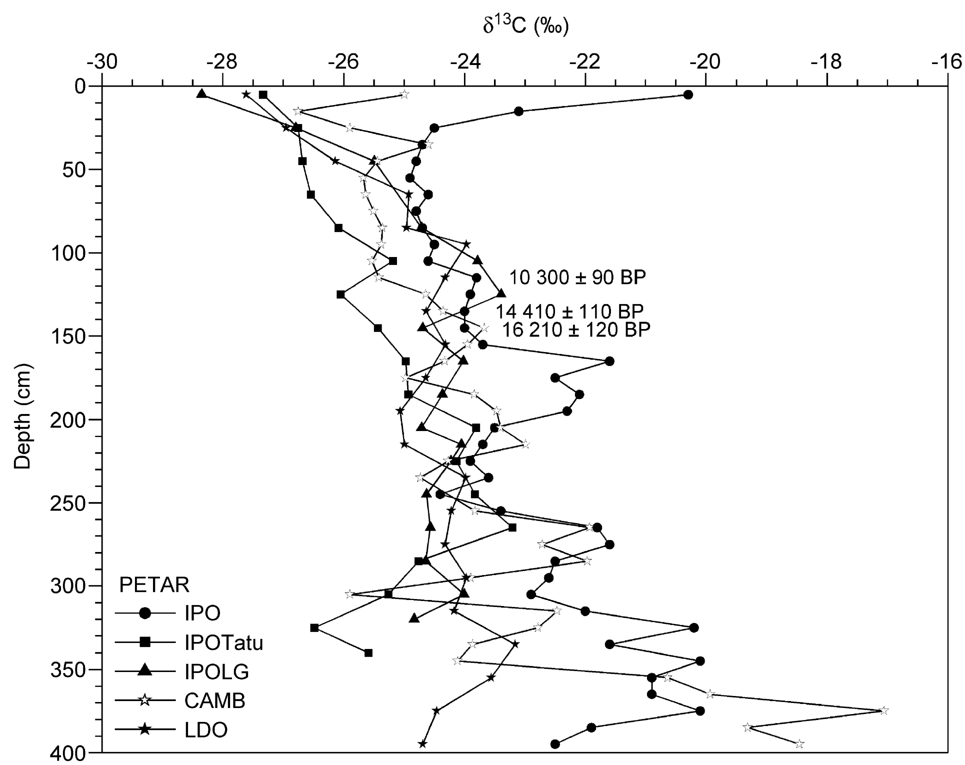

Fig. 3. $\delta^{13}C$ of SOM and ^{14}C dating of buried charcoal fragments collected in PETAR in relation to soil depth.

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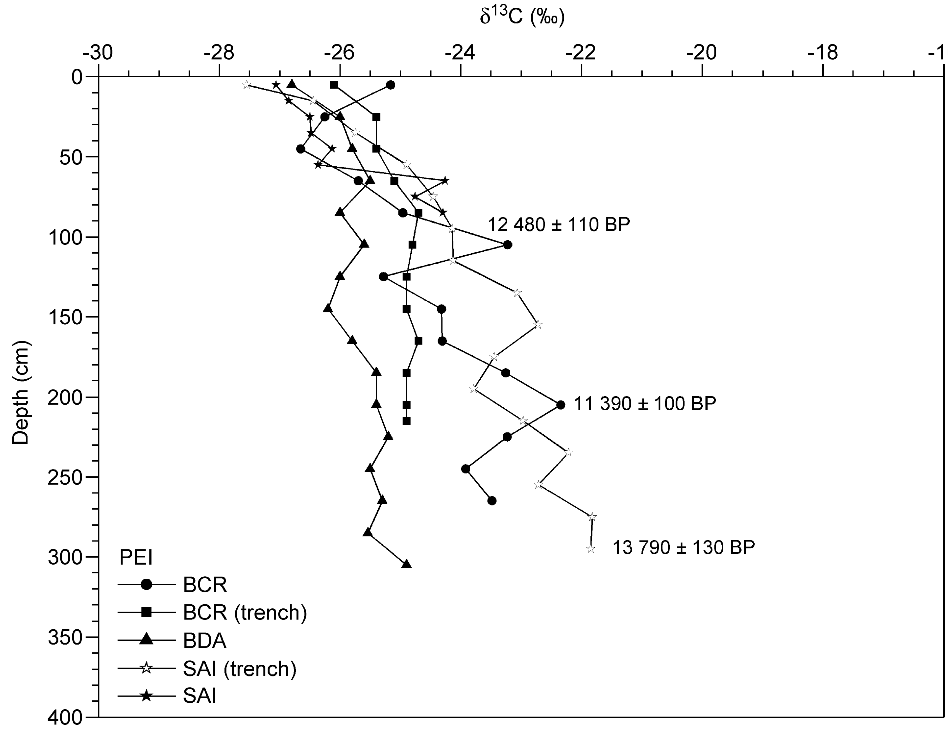

Fig. 4. $\delta^{13}C$ of SOM and ^{14}C dating of humin fraction of the PEI soils in relation to the depth. The radiocarbon ages of 12,480±110 yr BP and 13,790±130 yr BP were obtained at SAI profile and 11,390±100 BP at BCR profile.

isotopic fractionation that occurs during organic matter decomposition and with variations in the carbon isotope composition of atmospheric CO_2 (Nadelhoffer and Fry, 1988; Boutton, 1996). Variations larger than 4‰ were associated with changes in plant community (Cerri et al., 1985; Boutton, 1996; Desjardins et al., 1996).

The $\delta^{13}C$ values in relation to soil depth for the PETAR sites are presented in Fig. 3. The larger isotope changes are observed in the IPO and CAMB sites. Very enriched ^{13}C values, as high as −16‰, are observed in the deepest part of these profiles indicating these sites were colonized by C_4 plants suggesting the existence of open areas dominated by grasses. Enriched ^{13}C values around −22‰ are also observed at site IPO between 200 and 150 cm depths indicating the influence of C_4 plants probably related to an opening of the forest in the area around the IPO site. The rest of the data showed $\delta^{13}C$ values around −24‰ in all profiles, changing toward more depleted ^{13}C in the shallow part of the profile. The exception is site IPO that showed a shift toward more enriched ^{13}C values indicating the predominance of C_4 plants during the recent history at this site. The $\delta^{13}C$ patterns, with the exception of the sites IPO and CAMB, indicated that most of the PETAR area has been dominated by forest at least from ~20 ka yr BP. The presence of C_4 plants inferred from the $\delta^{13}C$ record obtained at IPO and CAMB sites suggested the existence of cooler and dry conditions during the late Pleistocene and early Holocene in the PETAR region. The dominance of the forest inferred from the $\delta^{13}C$ data suggests a change toward more humid and wet conditions during most of the Holocene.

The $\delta^{13}C$ data collected at sites BCR, BDA and SAI in the PEI soils are reported on Fig. 4. These data showed a trend from enriched ^{13}C values as high as −22‰ in the deepest part of the profiles toward depleted ^{13}C values reaching values as low as −28‰ in the shallow part of the profiles at SAI and BCR sites. The rest of the data collected at site BDA showed $\delta^{13}C$ values between −25‰ and −27‰ in the whole profile. These data suggests that only the area represented by the SAI and BCR sites had more influence of C_4 plants in the early part of the Holocene. The $\delta^{13}C$ data collected at the BDA site showed that forest was also present during the entire Holocene in the PEI region. These are similar patterns that the ones recorded at the PETAR region.

Evidence for climate and vegetation changes have also been reported in distinct locations of southern and southeastern regions of Brazil since the late glacial period. The isotopic soil records in small semideciduous forest fragments (~1.0–2.0 km²) in Londrina, ~350 km southwestern of PETAR and PEI and Piracicaba and Jaguariúna, ~300 km northeastern, showed the predominance of C_4 plants from the late Pleistocene to the early Holocene and the predominance of C_3 plants for the rest of the Holocene (Pessenda et al., 1996a, b, 1998c; Gouveia et al., 2002). Pollen analyses of lake sediments at Serra Negra, Minas Gerais, ~500 km northeastern, indicated a cooler and relative humid climate intersected by dry phases. For the period of ~30 to ~20 ka BP and ~13–10 ka BP, the climate was humid and very humid, respectively, with short dry phases (De Oliveira, 1992). Pollen records collected in Botucatu, São Paulo State, ~280 km northeastern, suggested the presence of savanna vegetation and colder and drier climate than the present between 48 and 18 ka BP (Behling and Lichte, 1997; Behling, 2002). The pollen data from peat samples at Morro de Itapeva, São Paulo State, ~450 km northeastern, inferred the presence of a cold and dry climate from ~35 to ~17 ka BP. From ~17 to 10 ka BP the presence of a warm climate was observed and during the Holocene more humid conditions were established (Behling, 1997).

In a preliminary study using soil $\delta^{13}C$ analysis in the coastal Atlantic Forest region, São Paulo State, distant ~260 km northeastern, Garcia (2003) observed an influence of C_4 plants in the past. In the same region in an ecosystem cloud forest-woody savanna-savanna of ~10 km, Pessenda et al. (2007) using carbon isotopes (^{13}C, ^{14}C) in soil and pollen and carbon isotopes analyses in a peat record, observed a mixture of C_3 and C_4 plants in the soil record and the presence of glacial elements and herbs in the peat record during the period of ~28 to ~13 ka BP. From ~13 ka BP to the present the predominance of C_3 plants in the soil records and the increase in the arboreal species in the peat record, were related with the presence of more humid climatic conditions than the previous period.

Vegetation and climate changes were also observed in tropical and subtropical lowlands in the South America during the late glacial and the Holocene. According to Ledru and Mourguiart (2001), the late glacial, the transition from the last glacial maximum (LGM) to the Holocene, is the key period for understanding the mechanisms of abrupt climatic change. During the interval 15.5–14.4 ka cal BP (~12.7–12.4 ka BP) conditions were wet in tropical and subtropical forest regions and dry in southern South America and along the Venezuela/southeast Caribbean coast. During the interval 14.4–12.7 ka cal BP (~12.4–10.9 ka BP) conditions became wetter in the South America. For the next period 12.7–11.4 ka cal BP (~10.9–9.8 ka BP), moist forests were well developed in the tropical and subtropical lowlands, showing few signs of short-term environmental fluctuations that might correlate with the well-documented climatic cooling in the circum-North Atlantic region.

5. Conclusions

Significant carbon isotope variations in SOM profiles reflecting changes in vegetation were observed at the Atlantic Forest located in the southern region of São Paulo State, southeastern Brazil. From ~20 to ~16–14 ka BP the presence of more open vegetation is indicated by the carbon isotope data, with the possibility of a mixture of C_3 and C_4 plants in at least three sampling locations at PETAR and PEI, probably associated with a drier climate than the present. From ~16 to 14 ka BP to the present the gradual predominance of C_3 plants was observed in all sampling locations probably associated with a continuous forest expansion related to more humid conditions than previously. The occurrence of a drier climate during the late Pleistocene to early Holocene in the region did not significantly change the dynamic of the forested ecosystem in the continental Atlantic Forest. Our results agree with pollen data from lake sediments and peat samples and carbon isotope data from peat and SOM samples from previous studies developed in the southern and southeastern regions of Brazil. Similar moist conditions were inferred in our study in comparison with data obtained from tropical and subtropical lowlands in South America in the period of ~12.7–9.8 and ~4.0 ka BP to present time.

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