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Palaeofires in Amazon: Interplay between land use change and palaeoclimatic events

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ABSTRACT

Interpreting the geological record of Amazon biomass combustion requires comparing charcoal accumulation rates in various biomes at different time scales. Charcoal accumulation rates, a proxy for palaeofire records, were obtained in sediment cores from Amazon lakes surrounded by several vegetation types and from a reservoirs in an intense land use change region. The records presented in this study were obtained in the following areas i) a reservoirs in Alta Floresta region (northern Mato Grosso State); ii) Lago do Saci (southern Pará State), a lake close to Alta Floresta and located at the southern border of Pará State; iii) a bog in an ecotone area in the Humaitá region (southern Amazonas State); iv) lakes in lateritic iron crust of the Carajás Hills (southeastern Pará State); v) Lago Comprido, a floodplain lake close to the Amazon River and surrounded by tropical rain forest (Monte Alegre, Pará State; vi) Lagoa da Pata in the Morro dos Seis Lagos alkaline complex (São Gabriel da Cachoeira, Amazonas State) and vii) Lago Caracaranã, a secluded lake in the northern Amazon cerrado (Roraima State). The highest charcoal accumulation rates were observed for modern records related to an intense change in land use at Alta Floresta, which had no precedent during the Holocene history of the Amazon. High charcoal accumulation rates that were observed in the Carajás region during low lake level phases in the Amazon in the mid-Holocene were comparable to those at the onset of the human settlement in Alta Floresta region. An increase in charcoal accumulation rate was observed in the late Holocene when the lake level was high, suggesting an interaction between climates and human presence. Low charcoal accumulation rates are typical of modern high rainfall environments, as observed in Lagoa da Pata where the environment is not susceptible to occurrences of wildfires even during relatively drier climatic phases. Low charcoal accumulation rates also exist in the relatively dry cerrado (savanna type) biome even during relatively dry phases in the Caracaranã region where the savanna-type vegetation biomass is lower and thus generates less charcoal particles than forest ecosystems.

1. Introduction

Charcoal can be associated with vegetation burns that result from both anthropogenic activities and palaeoclimatic changes. Its presence in geologic archives can therefore be used as an indicator and recorder of past impacts on continental biomass, one of the world's most important carbon pools and carbon sink ecosystems.

Studies of the carbon cycle during the LBA Experiment (Large-scale Atmosphere Biosphere Experiment in Amazonia) have indicated that the undisturbed forests of the Amazon region behave as a trap for carbon, with incorporation rates ranging from 1 to 7 tonnes per hectare per year. (Nobre and Nobre, 2002). Deforestation and biomass burning account for a net release of approximately 0.2 GtC of carbon per year in the Brazilian Amazon (Nobre and Nobre, 2002). Currently, 20 to 30% of global anthropogenic CO_2 emissions are sequestered by the terrestrial biosphere (Gurney et al., 2002) and the Amazonian ecosystems have been suggested as a major contributor to observed interannual

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variations in this sink (Bosquet et al., 2000). Great variability in the CO_2 sink is consistent with enhanced CO_2 removal during the wet and cold conditions associated with a strong La Nina condition, as observed from mid 2010 to March 2012 (Lê Quéré et al., 2013). Changes in the CO_2 sinks of the Amazon are highly uncertain, as they depend on the temperature and precipitation regimes. The Amazon terrestrial ecosystems vary from being a carbon source of 0.2 Pg C/year to acting as a carbon sink of 0.7 Pg C/year (Tian et al., 2000). Nepstad et al. (2004) pointed out that severe drought in Amazonia provokes large carbon emissions by increasing forest flammability and tree mortality and by suppressing tree growth. Intense droughts promote loss of forest biomass, reversing a large long-term carbon sink (Phillips et al., 2009). The exceptional growth in atmospheric CO_2 concentrations in 2005 may have been partially caused by the effects of Amazon drought (Phillips et al., 2009). Atmospheric measurements (Gatti et al., 2014) demonstrated that intact Amazonian forests are a substantial carbon sink during non-drought years. They may have a significant influence on future atmospheric CO_2 levels (Le Quéré et al., 2009) and may have had a significant biogeochemical influence on climatic variations during the Quaternary by behaving alternately as a carbon source or a carbon sink.

The Last Glacial Maximum (LGM, approximately 18,000 years ago) was characterised by a reduction in carbon stocks of various types in vegetation and soils around the world, including the South American ecosystems (Ab'Saber, 1977, 1982; Adams et al., 1990; Van Campo et al., 1993; Bird et al., 1994; Crowley, 1995; Adams and Faure, 1998; Behling et al., 2001; Mayle and Beerling, 2004; Turcq et al., 2002b). Behling et al. (2001) estimated a 40% reduction in the forested area and 20% decrease in the carbon stock in the Amazon region during the LGM compared to modern levels. Turcq et al. (2002a) emphasised the uncertainties in this estimate, estimating a reduction of between 6 and 56% of the carbon stock during this same period. Since the LGM, an expansion of tropical forests has been largely responsible for the increased carbon storage in terrestrial ecosystems when carbon fluxes from the ocean increased as a result of the decrease in CO_2 solubility and degassing from the oceans, with the carbon passing through the atmosphere and finally being taken up by the land ecosystems. This tropical forest increase is evident from comparison of the carbon stocks of the mid-Holocene and the present. For example, Behling et al. (2001) demonstrated an increase in the carbon stock in the tropics during the Holocene. Similarly, Adams and Faure (1998) estimated that the present carbon stock is 115 GtC larger than during the mid-Holocene (8000 to 5000 cal years BP).

The occurrence of fires is a factor that determines changes in carbon stocks and plant communities (Bond et al., 2005) and when associated with dry climates has been a mechanism that caused a massive transfer of carbon from forest ecosystems to the atmosphere (e.g. the CO_2 increase after 8000 cal years BP recorded in Taylor Dome, Antarctica, Indermühle et al., 1999). The presence of charcoal as an indicator of vegetation burning has been found in soils (Soubies, 1980; Sanford et al., 1985; Saldarriaga and West, 1986; Bassini and Becker, 1990; Piperno and Becker, 1996; Pessenda et al., 1998a; Santos et al., 2001; Hammond et al., 2006) and lake sediments (Sifeddine et al., 1994; Cordeiro, 1995; Cordeiro et al., 1997; Irion et al., 2006; Bush and Silman, 2007; Bush et al., 2007; Cordeiro et al., 2008) at various Amazonian sites and has been interpreted classically as a consequence of dry climates associated with increasing human presence.

This overview aims to relate changes in Amazon charcoal accumulation rates during the last 50,000 cal years BP and the extent of fire occurrences by comparing charcoal accumulation rates, evidence of palaeoclimatic changes on various time scales, and records of land use change. The charcoal accumulation rates in each palaeoenvironmental record were interpreted as a function of bulk organic carbon accumulation rate and its source as an indicator of palaeohydrological changes. Fire and palaeohydrological records were obtained from charcoal particles and organic matter elemental/isotopic analyses in sediments lakes and man-made reservoirs in a region of intense land use change at Alta Floresta in Mato Grosso state; Lago do Saci in southern Pará State 100 km away from Alta Floresta City, a bog in the ecotone region at Humaitá (southern Amazonas state), lakes in Carajás Mountains Serra Sul and Serra Norte (Pará State), Lago Comprido in the Para State, an Amazon River floodplain lake, Lagoa da Pata at Morro dos Seis Lagos (São Gabriel da Cachoeira, northern Amazonas State) and Lago Caracaranã (Roraima State).

2. Study areas

The locations of the seven study areas are shown in Fig. 1 and are described below.

2.1. Alta Floresta region (MT)

The city of Alta Floresta, founded in 1976, is located in a plain, 280 m altitude, on the Central Crystalline Plateau in an area occupied by dense tropical forest. Population increased rapidly in the 1980s due to gold mining and logging activity. This region is characterised by a humid tropical climate with an intense dry season between June and August. The annual mean precipitation is approximately 2600 mm (Oliveira and Albuquerque, 2005). The best time series obtained for the region of Alta Floresta show averages, maximum and minimum annual temperatures of 26.3 °C, 33.5 °C and 18.8 °C respectively. The vegetation is composed of open and dense tropical rainforest, seasonal forest, and cerrado (savanna type, RADAMBRASIL, 1975). Six cores were collected from flooded areas behind man-made dams in 2005 to analyse the impacts of land use changes. Data from five cores, L-cen050 (9°53′5.32″S, 57°24′13.43″W), L-ssw100 (10°26′4.16″S, 56°26′10.93″W), L-wnw150 (9°47′31.70″S, 57°24′13.43″W), L-ssw150 (10°41′44.66″S, 56°35′36.78″W), and L-wsw150 (9°58′17.51″S, 57°5′54.53″W), are discussed in this contribution. Also discussed are the data from core AT 1a (9°58′S, 55°49′W), which was collected in 1996 (Cordeiro et al., 2002) also from an impoundment behind a dam.

2.2. Lago do Saci (South of Pará state)

Lago Saci is located in southern Para State in an area of the Central Plateau of Brazil, where crystalline rocks of the Brazilian Shield are exposed. The lake is located 1.5 km north of the São Benedito River and 100 km north of Alta Floresta (MT) (Fig. 1). The area is characterised by a humid climate with a very intense dry season between June and August, with temperatures ranging between 23 °C and 37 °C and an average annual rainfall of 1800 mm. Lago do Saci is situated in a forested area (RADAMBRASIL, 1975). Today, there is no connection between the lake, which is a black water lake, and the São Benedito River. The Saci 1 cores were collected from the deepest part of Lago Saci, at 9°7′0.37″S and 56°16′9.85″W.

2.3. Humaitá área (AM)

The core was collected from a bog at 8°10′00″S; and 63°46′56″W in a depression on an extensive flooded plain at the Três Coqueiros farm in the Humaitá region. This area in southwestern Amazonia has been intensively discussed in relation to dynamics between three vegetation types forest, cerrado, and field during the Holocene (Pessenda et al., 1998a,b). The annual mean precipitation is approximately 2500 mm, and the annual mean temperature is 26 °C. An expansion of soybean cultivation characterises this region, which is located in the “Arc of Deforestation”.

2.4. The region of Serra dos Carajás

Serra de Carajás, or the Carajás Range, is located at the southern limits of a dry corridor between two regions of intense rainfall in Amazonia. The western region is the area of maximum convective

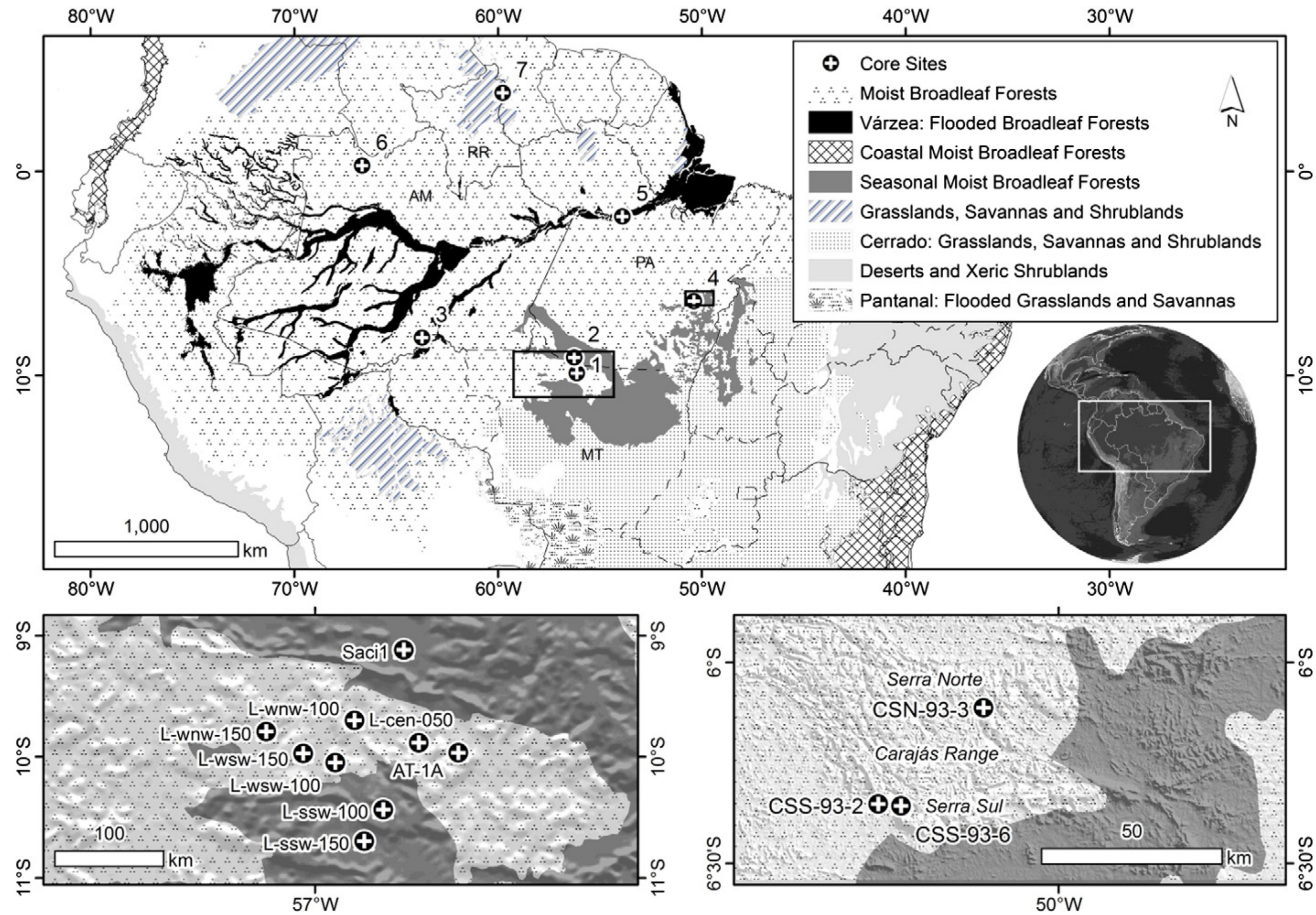

Fig. 1. Geographic locations of the sampling point study sites. 1: Alta Floresta region shown in greater detail the position of the six short cores in the square below left; 2: Rio São Benedito region, Lago Saci; 3: Humaitá region (Amazonas State), HUM-97-5 core; 4: Carajás site (Pará State), CSS93/2, CSS93/6 (Elias et al., 2001), CSN93/3 (Cordeiro et al., 2008), CSS93/2 (new data set) shown in greater detail in the square below right; 5: Monte Alegre region (Pará State), Lago Comprido; 6: Morro dos Seis Lagos, São Gabriel da Cachoeira region (Amazonas State) (more detail of the sampling point in Cordeiro et al., 2011); and 7: Caracaranã region, Lago Caracaranã (Roraima State).

rainfall. This rainfall is related to the position of the Intertropical Convergence Zone and onshore sea breezes. According to Silva et al. (1986, 1996), the average rainfall in Carajás is 2126 mm, and the average annual temperature ranges from 23.5 °C (at an elevation of 835 m) to 26.2 °C (at elev. 203 m).

The cores were collected from a lake named N4 that is located on a lateritic plateau of Serra Norte de Carajás (5°50′ to 6°35′ S lat and 49°30′ to 52°00′W long) at an elevation of 800 m (Fig. 1) and from two lakes in the Serra Sul of Carajas; core CSS-93-6 (6°21′25.22″S lat and 50°23′35.86″W long), and core CSS-93-2 (6°21′8.66″S lat and 50°26′59.09″W long). The vegetation is rain forest, including closed and open rainforests, and open ground (campos rupestres) according to Silva et al. (1986, 1996) that developed on top of an iron-rich soil and are linked to edaphic constraint on this soil, and hydroseral vegetation (Silva and Cleef, 1989), represented by aquatic and swamp vegetation.

2.5. Lago Comprido

Lago Comprido (Comprido Lake), located near the city of Monte Alegre, Pará, and on the south bank of the Amazon River 500 km from the estuary, has an indirect connection with the Amazon River. This lake has an area of 16 km^2, and during high water periods, it is connected to the main river channel through Lago Maracá. During low water periods, the lake is completely isolated from the Amazon River. The catchment area is characterised by a humid tropical climate without long dry periods. The annual mean precipitation is approximately 2200 mm, and the annual mean air temperature is approximately 27 °C (RADAMBRASIl, 1975). The lake is bounded by a dense tropical rain forest (terra firme forest) on the southern bank and a forest-savanna transition on the northern bank (RADAMBRASIL, 1975). The core COM1 was collected by hand at 02°12′18.5″/W53°54′01.8″(Fig. 1) at a water depth of 1.8 m., about 12.5 km from the main channel of the Amazon River, and around 600 m from the lake margin.

2.6. Morro dos Seis Lagos, upper Rio Negro region (AM)

Morro dos Seis Lagos is located at 0°16′N and 66°41′W, in northern Amazon State, Brazil. This site is inside Pico da Neblina National Park and is located 100 km north of the city of São Gabriel da Cachoeira, northwest of Manaus, the state capital.

The area of Alto Rio Negro, where Morro dos Seis Lagos is located, is characterised by a plain at an average elevation of 75 m. The lateritic crust has a surface with several collapse depressions, a structure known as Morro dos Seis Lagos Lagoa da Pata, which is approximately 400 m long and 4 m deep, occupies a closed depression at an elevation of approximately 360 m a.s.l.. The vegetation in the plain area surrounding the hill is dense tropical forest (floresta ombrofila densa) that is developed on extremely poor soils. The climate in the area is hot and humid, lacks a dry season, and has a total annual precipitation of approximately 2900 mm. The area experiences a decrease in precipitation from July to November. The least wet month is September, when approximately 150 mm of precipitation falls. Details on the lake sediment stratigraphy and palynology have been previously published (Colinvaux et al., 1996a). Core LPT V, which will be discussed below, was collected at 0°17′11.22″N and 66°40′36.18″W.

2.7. Lago Caracaranã — lavrados region (cerrado) of Roraima State (RR)

This site belongs to an extensive boundary area located in an ecotone where the tropical Amazonian forest suddenly changes to open grassland fields stippled by small palm tree creeks (Cerrado, Savanna type vegetation); this transition area is locally known as lavrados. These cerrado cover extensive lands in northeastern Roraima State (northern Amazon). The forest-cerrado boundary is geographically constrained between 2° and 5°N and 59° and 62° W and is a mosaic of vegetation assemblages with cerrado enclaves in forested areas and vice-versa (Sanaiotti, 1997). The modern climate is warm, with a strong dry season up to 6 months long. In a regional context, the lavrados of Roraima are located at the end of a NE-trending dry corridor that crosses the Amazon plain from the south side of Pará State to the south-central part of Roraima State. The study area is located in the driest portion, with annual rates of precipitation grading from 1100–1400 mm/year in the lavrados to 1700–2000 mm/year in the seasonal forest and up to 2200–3500 mm/year in the broadleaf forest in the south, near the boundary with Amazonas State (Barbosa, 1997). The Lago Caracaranã is located in the northern portion of these transition corresponding to the coordinates 3°51′N and 59°48′W, close to the border with the Guiana.

3. Materials and methods

3.1. Core collection

Short cores, which contain a recent record, i.e., the last hundred years, and long cores, which contain a record of the last several thousands of years, were respectively collected manually and by a vibro-core system developed by Martin et al. (1995) in lakes from Carajás region (PA) and Lago Saci (PA). The cores from Lagoa da Pata (AM) were collected using a piston core coupled to an advancing mechanism developed by Antonio Rommanazi (GEOLEMN, Department of Geochemistry, UFF). A lightweight transportable float for use in the jungle was developed specifically for the expedition. The cores from the Carajás, Comprido and Alta Floresta lakes were collected manually by advancing an aluminium tube into the sediment. All of the cores were collected using aluminium tubes 7.5 cm in diameter. The cores were extruded and then sliced into sections for analysis.

3.2. Sedimentological analyses

Shortly after the opening of the core, each sample was dried at 40 °C to constant weight. Aluminium U channels were used to determine sediment bulk density. The moisture content and bulk density of each section were determined based on the differences between the wet and dry weights. The bulk density data were used to calculate the accumulation rate of the analysed variables through the product of the bulk density, sedimentation rate (calibrated ages), and the element concentrations.

3.3. Core chronology

The geochronology of the Alta Floresta short cores was determined using the ^{210}Pb method and historical landsat images between 1978 and 2006 to visualize when the dams were built to better interpret the chronologies. The chronology was determined by the ^{210}Pb analyses and stratigraphic data considering the contact of the top layer of soil from before the dam flooding and the base of the organic sediment deposition after flooding. The sedimentation rate was calculated using the CIC method (constant flux and sedimentation).

The chronologies of the long cores were determined using the accelerator mass spectrometry technique (AMS). The ages were calibrated using the Calib 5.0.2 programme (available at http://radiocarbon.pa.qub.ac.uk/calib/) and expressed in cal years BP. Ages older than 16.000 cal years BP were calibrated using the age model proposed by Fairbanks et al. (2005) at the CAL Pal programme (Weninger and Jöris, 2007).

3.4. Charcoal particle analysis

The method for quantifying the charcoal and other microscopically identified particles was as follows: one gram of moist sediment samples was subjected to alkaline extraction using a 10% sodium hydroxide solution. The samples were treated with the solution as many times as necessary until the supernatant was clear. The sediment samples treated with the alkaline solution were washed with distilled water and stored in a 100-ml water solution. From the 100-ml solution, 2 ml were taken during agitation and then filtered through an acetate cellulose filter (Millipore, HAWP 24 mm, and 0.45 μm porosity). The filter was dried, weighed and then glued with ethyl acetate on plexiglas sheets. Either twenty fields were counted, or a sufficient number were counted to reach a minimum of 30 particles of each type. The sizes of the particles were measured, including the length and width of each particle counted. The charcoal particles counted have the following characteristics: Angular forms, size between 2 and 350 μm, and the particles are distinguished from other shaped carbonaceous elements by their capacity for reflection in reflected light.

The method used herein differs from other quantification methods due to the measurement of the sediment mass via the filter weight. Weighing of the filters allowed for quantification of the particle mass relative to the sediment dry weight and calculation of the accumulation rate. The charcoal accumulation rate (CHAR) was calculated using the following formula: CHAR (particles/cm^2/years) = charcoal particle concentration (number of particles/g) × bulk density (g/cm^3) × sedimentation rate (cm/yr).

3.5. Organic matter elemental and isotopic analyses

Determinations of total organic carbon and nitrogen and ^{13}C of the sediment samples were obtained using a mass spectrometer coupled to an automatic analyser of carbon and nitrogen in the following laboratories.

a) The samples from Lago Comprido, Lago do Saci, and Humaitá bog were analysed at the UC Davis Stable Isotope Facility Department of Agronomy at the University of California.
b) The samples from Lagoa da Pata were analysed at the Environmental Isotope Laboratory, University of Waterloo, Canada.
c) The samples from Caracaranã, Carajás and Alta Floresta were analysed at the Programme of Geochemistry at Fluminense Federal University in a Perkin Elmer CHN automatic analyser.

4. Results and regional discussion

4.1. Increase in charcoal deposition in an area of intensive land use change in the Brazilian Amazon (Alta Floresta, MT)

In the Alta Floresta region, the six cores (Fig. 2) show similar increases of charcoal accumulation rates during the period of population growth. In the Amazon region, the population generally grows after the construction of a road (Fearnside, 1987). The largest charcoal accumulation rate peak, considering land use changes and palaeoclimatic record, occurred in 2000 and reached 2.83×10^7 particles cm^{-2} years^{-1} and corresponding to a quick population growth. This peak was observed

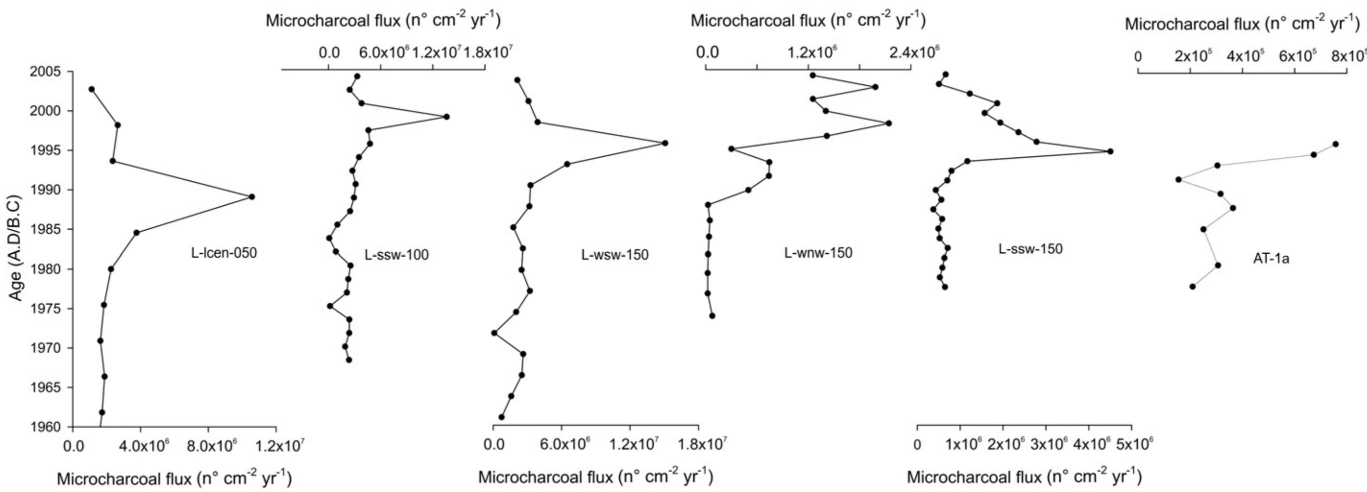

Fig. 2. Increases in microcharcoal accumulation rates in man-made reservoirs following colonisation since the 1970s in the Alta Floresta region (North Mato Grosso state).

in core LCEN050 and precisely delineates the point nearest the city centre where the impacts of land use were most intense. The mean charcoal accumulation rates are 6.02×10^6 particles cm^{-2} years^{-1} in core L-lcen050 with a peak of 1.06×10^7 particles cm^{-2} years^{-1} in 1989 AD, 4.31 × 106 particles cm^{-2} years^{-1} in core L-ssw100 with a peak of 1.36 × 107 particles cm^{-2} years^{-1} in 1999, 3.34×10^6 particles cm^{-2} years^{-1} in core L-wsw150 with a peak of 1.51×10^7 particles cm^{-2} years^{-1} in 1996 DC, 7.07×10^5 particles cm^{-2} years^{-1} in core L-wnw 150 with a peak of 2.14×10^6 particles cm^{-2} years^{-1} in 1998 DC, 1.14×10^6 particles cm^{-2} years^{-1} in core L-ssw150 with a peak of 4.51×10^6 particles cm^{-2} years^{-1} in 1994 DC, and 3.37×10^5 particles cm^{-2} years^{-1} in core At1a with a peak of 7.57×10^5 particles cm^{-2} years^{-1} in 1995.

Core SSW150 exhibits a peak just after the construction of a dam and reflects the beginning of the population growth described by Bosco-Santos et al. (2013). The gap observed between the cores is most likely due to the local patterns of occupation (Fig. 2).

4.2. Charcoal deposition in Lago Saci in a evergreen forest/semideciduous forest transition area

Martins (2012) report low values of TOC and chlorophyll derivatives and an abundance of Poaceae pollen in the Lago Saci sediment record between 35,000 and 18,300 cal years BP that suggest a period of dry climate. This period is accompanied by an increase in the charcoal accumulation rate, particularly between 35,000 and 25,000 cal years BP (Fig. 3). The average rate then was 6.03×10^3 particles cm^{-2} years^{-1}, whereas the rate between 25,000 and 18,000 cal years BP was higher, reaching, 9.02×10^4 particles cm^{-2} years^{-1}. A transition to a warm, wet climate during the late Holocene is indicated by the formation of a *Mauritia* palm swamp accompanied by a decrease in Poaceae pollen (Martins, 2012; Fontes, 2013). The charcoal accumulation rate increased substantially during the Holocene most likely due to an increase in the biomass (Fig. 3). Early to mid-Holocene climate was drier than the following period, with low TOC values, a higher influence of C4 vegetation and higher concentrations of black carbon and charcoal,

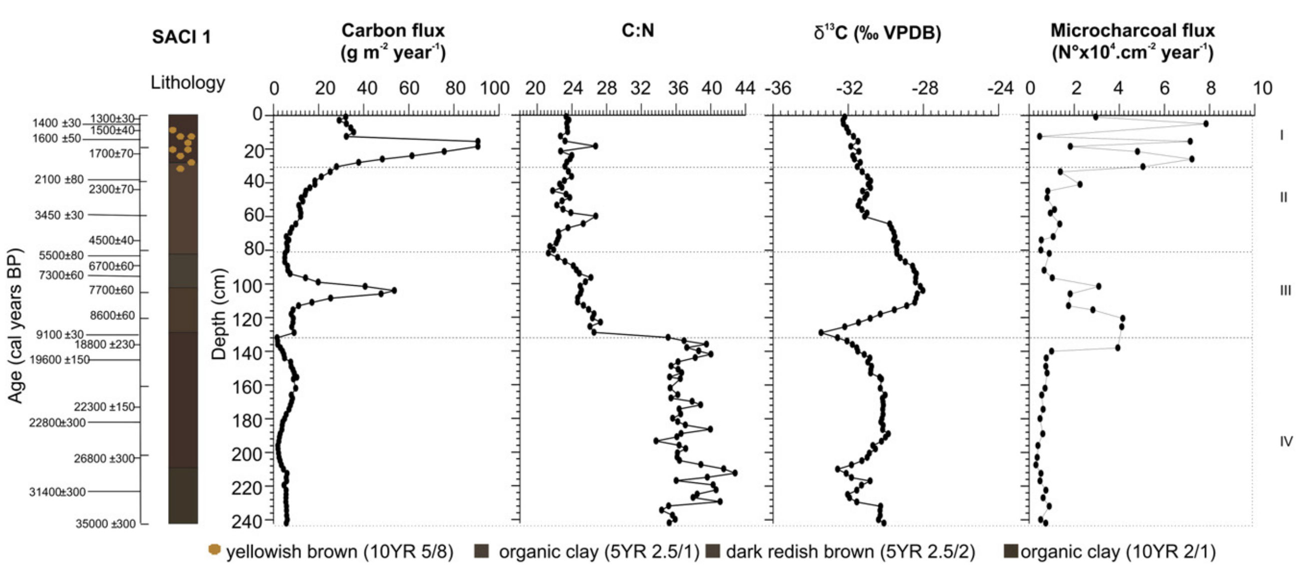

Fig. 3. Carbon accumulation rate, C/N ratio, δ^{13}C‰ and microcharcoal accumulation rate in sediments of Lago Saci, São Benedito II river region (southern Para state) during the last 35,000 cal BP. Organic carbon data from Martins (2012).

which accumulated at a rate reaching 3.87×10^4 particles cm^{-2} $years^{-1}$ between 8000 and 4500 cal years BP. The following time period between 4500 and 1500 cal years BP the charcoal accumulation rates decreased substantially, with values of approximately 1.38×10^4 particles cm^{-2} $years^{-1}$ (Fig. 3).

During the late Holocene, higher TOC and chlorophyll derivatives indicate a wetter climate (Martins, 2012), as was also observed in records from elsewhere in the Amazonian basin. Charcoal accumulation rate reaches the highest values of 5.09×10^4 particles cm^{-2} $years^{-1}$ between 1500 cal years BP and the present, most likely due to the effects of a dry climate, high forest biomass and increased human activities.

4.3. Palaeoenvironmental history and charcoal deposition in vegetation transition zone in the Humaitá region

Vegetation in the Humaitá region is characterised by transitions between ombrophylous dense tropical forest vegetation, cerrado, and grassland vegetation during the Holocene, as identified using isotope analysis of soil organic matter (Pessenda et al., 1998a). Five phases are recognized (Carvalho, 2006) from the proportion and accumulation rate of biogenic elements (Fig. 4). 1) Between 4800 and 4600 cal years BP and corresponding to the end of the mid-Holocene dry phase, average organic carbon accumulation rate was low at 3.94 g cm^{-2} $years^{-1}$ compared to other phases in the core, indicating a low lake water level. A C/N ratio of 14.8 and an average $\delta^{13}C$ value of −23.8‰ indicate a mixture of autochthonous and allochthonous sources of organic matter. Charcoal accumulation rate reached 3.14×10^4 particles cm^{-2} $years^{-1}$ characterizing a dry phase with a common occurrence of fires. 2) 4600 to 3500 cal years BP, a wet phase characterised by relatively high values of organic carbon accumulation rate reaching 8.59 g cm^{-2} $years^{-1}$, with a lower C/N ratio in relation to other phases with 14.1, representing the flooding of the system with increasing algal production of organic matter. The average value of $\delta^{13}C$ −23.8‰ is close to that observed in the preceding phase. Charcoal accumulation rate decrease between 4600 and 3500 cal years BP, with an average of 1.55×10^4 particles cm^{-2} $years^{-1}$ interpreted to be the result of a humid phase, indicated by an increase in water level. 3) Between 3500 and 400 cal years BP, a decrease in the water level was interpreted (Fig. 4). The average value of total organic carbon accumulation rate for this period was 1.14 g m^{-2} $years^{-1}$, the lowest value considering the identified phases. The $\delta^{13}C$ value increased by ~1.3‰ to an average value of −22.2‰. These changes suggest decreasing water levels, favouring the development of C4 type vegetation. It should be noted that a significant increase in $\delta^{13}C$, reaching −19.3‰, was observed at 1660 cal years BP, indicating that the carbon isotopic variation may be related to an increased input of organic matter from grasses (C4). C4 type vegetation becoming more common results in a decrease of the biomass indicating that grass vegetation contributed to the lowest charcoal accumulation rate from 1660 to 1400 cal years BP. 4) From 400 cal years BP until the present an increase in the lake water level is suggested by high organic carbon accumulation rates, reaching the highest average values in the sequence of 12.6 g m^{-2} $years^{-1}$. An increase in algal organic matter typical of flooded environments is indicated by low C/N values and average $\delta^{13}C$ values that decreased by approximately 1.5‰ (average $\delta^{13}C$ = −23.8‰). The average organic carbon accumulation rate increased during approximately the last 300 cal years BP compared to the preceding phase, with a mean value of 12.6 g m^{-2} $years^{-1}$. A charcoal accumulation rate peak of 7.87 particles cm^{-2} $years^{-1}$ represents a wet phase with a high occurrence of fires, most likely corresponding to the development of present-day vegetation with high biomass and to the impact of human settlements (Fig. 4).

4.4. Palaeoenvironmental evolution and charcoal deposition in Serra dos Carajás during the Holocene. Comparison between the two mountain ranges (Serra Sul and Serra Norte)

Several studies of the geochemical, palynological and charcoal records providing insight into the environmental history of the region of Carajás (PA) have been published (e.g. Cordeiro et al., 1997, 2008; Turcq et al., 1998; Elias et al., 2001; Sifeddine et al., 2001; Hermanowski et al., 2012). An integration of all of the published core data (Cordeiro et al., 1997, 2008; Turcq et al., 1998; Elias et al., 2001; Sifeddine et al., 2001) and new unpublished data results in identification of the following phases (Fig. 5a and b). The period from ca. 11,800 cal years BP to 4000 cal years BP is characterised by a strong input of clastic mineral material into the lakes associated with low lake levels (Elias et al., 2001; Cordeiro et al., 2008), based on

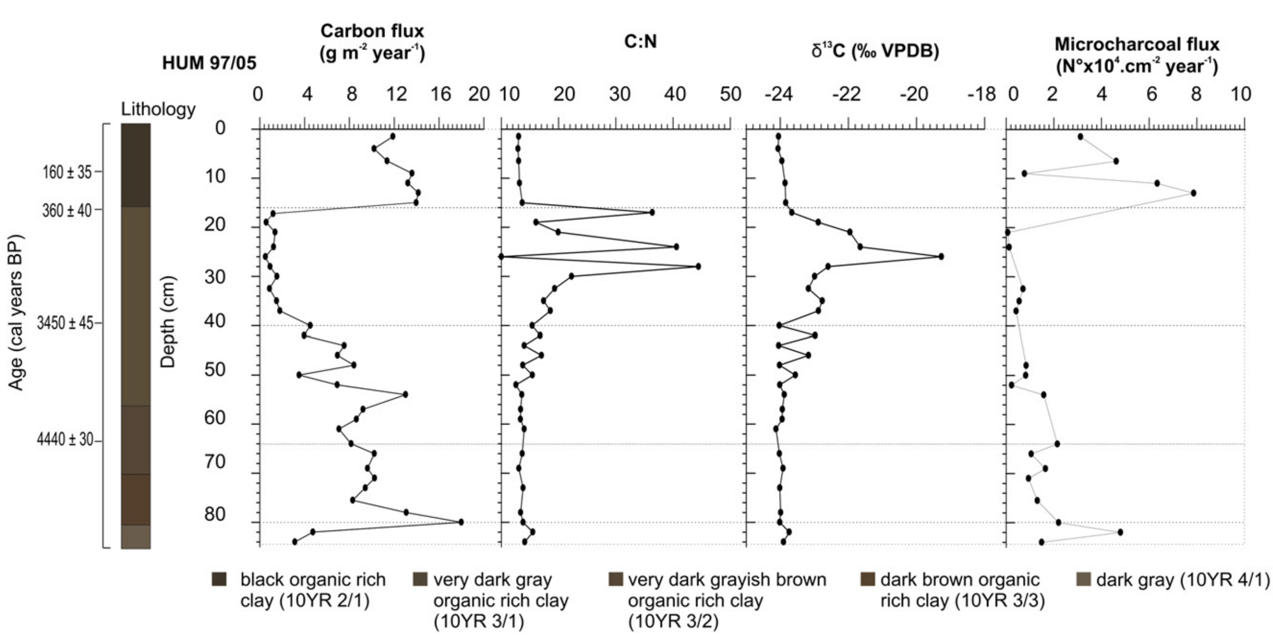

Fig. 4. Carbon accumulation rate, C/N ratio, $\delta^{13}C$‰ and microcharcoal accumulation rate in a lake situated in a depression area in ecotone (transition between forest, cerrado and fields) of Humaitá region (southern Amazonas state) during the last 4000 cal BP.

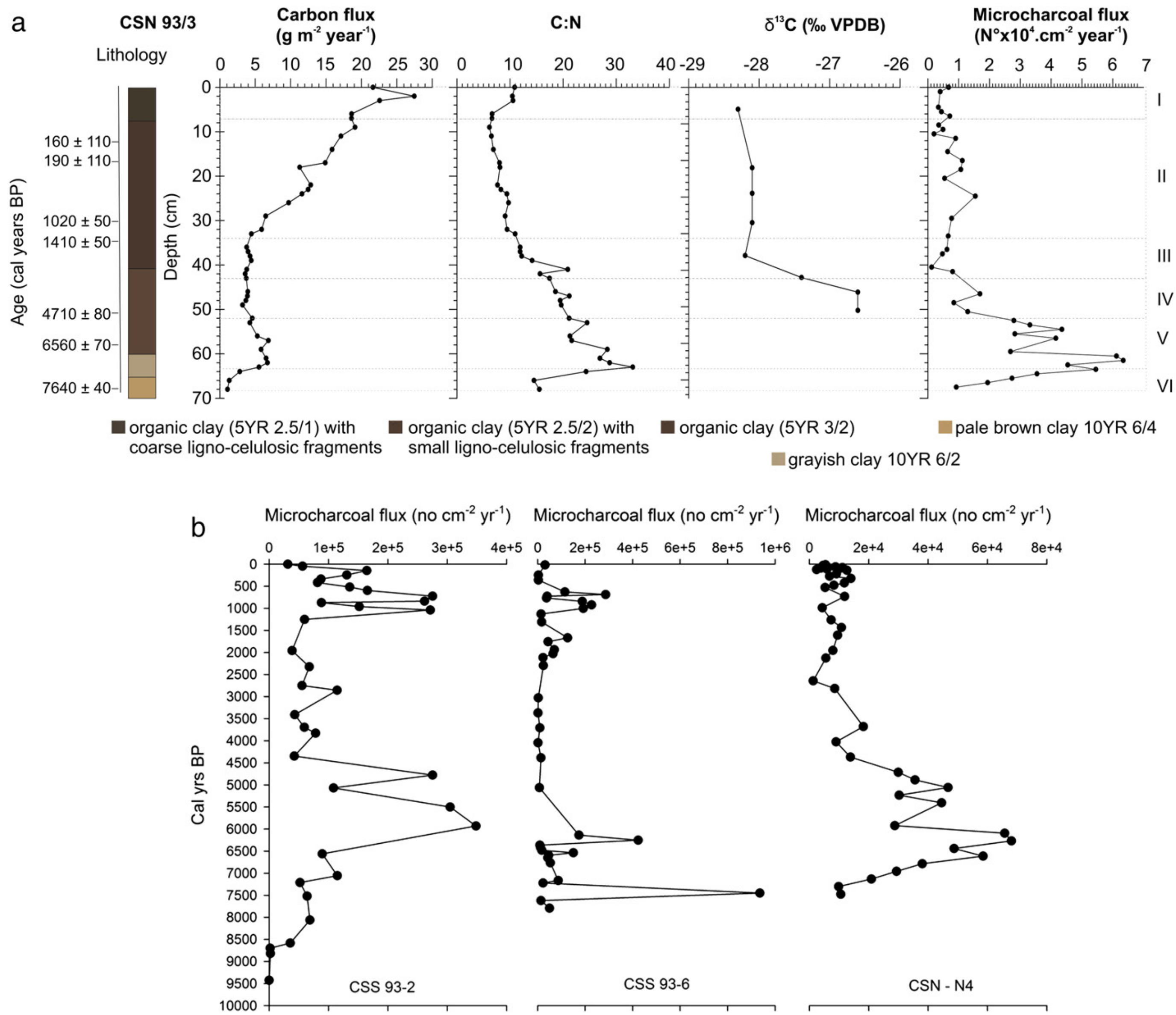

Fig. 5. a) Carbon accumulation rate, C/N ratio, $\delta^{13}C$‰ and microcharcoal accumulation rate in N4 Lake situated in Serra Norte Carajás (North sector, Carajás, PA), which was surrounded by a mosaic of tropical rain forest and steppe vegetation during the Holocene (ages calibrated interpolated), based on core CSN-93-3. b) Comparison between charcoal accumulation rates in three lakes in Carajás region. Cores CSS-93-6 and CSS-93-2 from Serra Sul (South Sector, Carajás, PA) and core CSN-93-3 (North sector, Carajás, PA).

palynological and geochemical analyses of the south range lakes (Serra Sul) (Absy et al., 1991; Elias et al., 2001; Sifeddine et al., 2001). Grain size and mineralogical sediment analyses, as well as pollen, spore and microscopic charcoal from Pántano da Maurítia in the Serra Sul dos Carajás reveal the presence of disturbed forest vegetation during periods of low lake levels that is attributed to the development of a strongly seasonal climate between 10,200 and 3400 cal years BP (Hermanowski et al., 2012). In the north range (Serra Norte), the accumulation rates of total organic carbon and sedimentary pigment derivatives were low, also indicating a low lake level (Cordeiro et al., 2008). The low accumulation rate of charcoal until 7600 cal years BP indicates a sparse occurrence of forest fires. Between 7600 cal years BP and 4750 cal years BP, the rate of accumulation of clastics decreased (Fig. 6). The accumulation rates of total organic carbon and sedimentary pigment derivatives (Cordeiro et al., 2008) remained low. There was burning of large amounts of biomass, as indicated by a high charcoal accumulation rate primarily between ~8000 cal years BP and 4500 cal years BP. The differences in charcoal accumulation rate and the range of the events between the tree cores could be attributed to regional patterns or imprecision in age determinations. The highest values were observed in three cores: $1.47 \times 105 \pm 1.16 \times 105$ particles cm^{-2} $years^{-1}$ in core CSS-93-2, $1.36 \times 105 \pm 2.46 \times 105$ particles cm^{-2} $years^{-1}$ in core CSS-93-6 both in Serra Sul and $3.77 \times 104 \pm 1.78 \times 104$ particles cm^{-2} $years^{-1}$ in core CSN-93-3 in Serra Norte. From ca. 4500 cal years BP to 1500 cal years BP, the average accumulation rate of charcoal particles was still high, based on core CSN-93-3, but lower values occur in the other two cores from Serra Sul. During the period from 2800 cal years BP to 1500 cal years BP, lacustrine production increased, as indicated by the increased sedimentary pigment derivatives (Cordeiro et al., 2008) and decrease in C/N ratio, most likely due to an increase in the lake level as observed in core CSN-93-3. The charcoal accumulation rate was low from ca. 1500 cal years BP to the present in the Serra Sul core. High charcoal accumulation rates, reaching 1.40×10^5 particles cm^{-2} $years^{-1}$

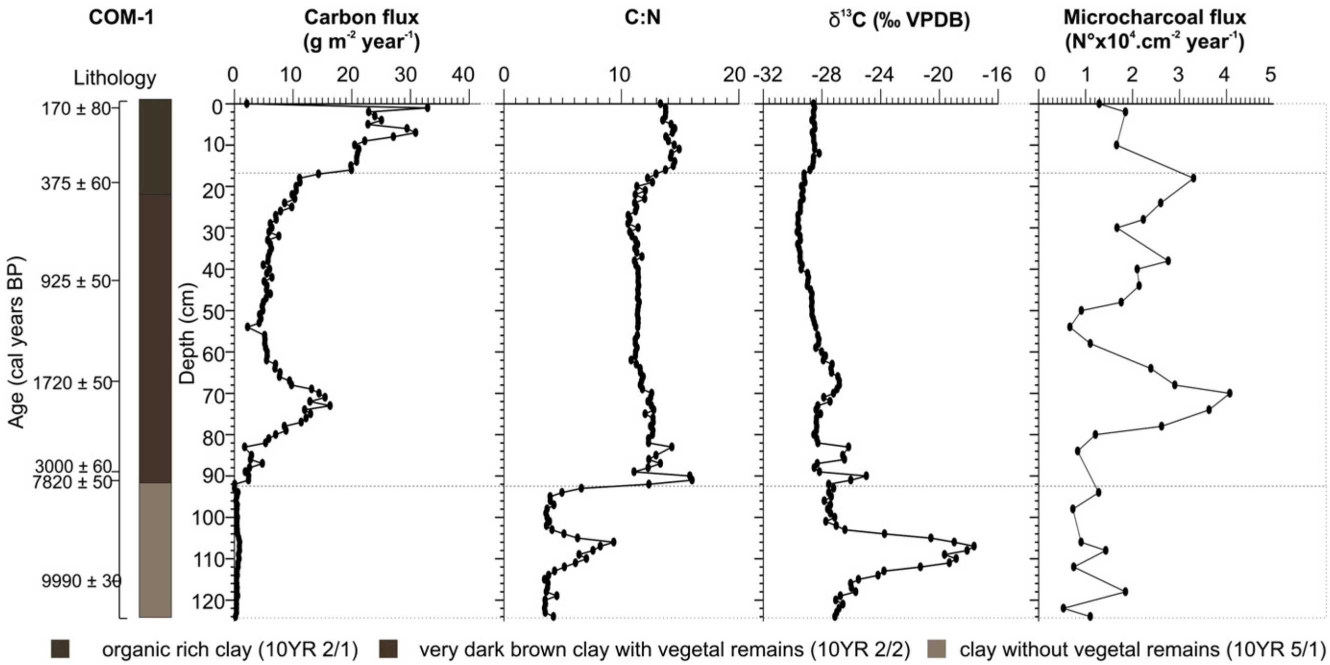

Fig. 6. Carbon accumulation rate, C/N ratio, δ^{13}C‰ and microcharcoal accumulation rate in Lago Comprido in the floodplain of the Amazonas River, (Monte Alegre, Pará State).

in CSS-93-2 core and 9.63×10^5 particles cm^{-2} years^{-1} in core CSS-93-6 were observed. Carbon accumulation rate rises, indicating an increased lake level due to a more humid climate. Episodic dry events occurred, accompanied by episodic forest fires. From ca 70 cal years BP to the present, core CSN-93-3 is characterised by the highest accumulation rate of TOC and sedimentary pigments (see Cordeiro et al., 2008), indicating a high lake level. A low charcoal accumulation rate was observed during this period (Fig. 5a).

4.5. Holocene palaeohydrological changes and charcoal deposition in a Rio Amazonas floodplain: Lago Comprido

During the early Holocene, a dry climate was suggested in the Lago Comprido sediment record by the presence of C4 plants and low amounts of TOC (Fig. 6) and chlorophyll derivatives (Moreira et al., 2013a). The charcoal accumulation rate is relatively stable and low during this period at a mean rate of 1.25×10^4 particles cm^{-2} years^{-1}. The mid-Holocene was represented by a break in sedimentation due to a complete drying of the lake caused by drier climatic conditions, and this event has been observed in various features in the Amazon Basin (Absy et al., 1991; Pessenda et al., 1998a; Turcq et al., 1998; Mayle et al., 2000; Freitas et al., 2001; Behling, 2002; Cordeiro et al., 2008). The late Holocene was characterised by a wetter climate, with a gradual increase in the TOC (Fig. 6), chlorophyll derivatives and Aulacoseira sp. (Moreira et al., 2013a). Climate remained humid throughout the late Holocene in this region, and the last 3000 cal years BP were characterised by the highest lake levels. Although the evidence indicates a humid climate during the last 2000 cal years BP, the charcoal flux was relatively high, with mean values of 2.08×104 particles cm^{-2} years^{-1} and a maximum value of 4.07×104 particles cm^{-2} years^{-1} at 1700 cal years BP (Fig. 3). The high charcoal flux during the last 2000 cal years BP suggests a synergistic effect between human activity and climatic changes. In the city of Monte Alegre, near Lago Comprido, Roosevelt et al. (1996) found evidence of human occupation beginning 11,300 cal years BP. At Lago Comprido, this influence was especially evident after 2000 cal years BP. Considering the proximity of this location to a primary transportation route crossing the Amazon River and a nearby settlement, there is a very high likelihood of finding a long record (thousands of years) of disturbance, as discussed by Bush et al. (2007).

4.6. Palaeohydrological changes and charcoal deposition in a humid Amazon region during the last 50,000 cal BP: Lagoa da Pata, Morro dos Seis Lagos

In recent years, many findings from ice cores have indicated significant changes in temperature associated with changes in atmospheric composition. The most notable changes occurred between glacial and interglacial periods (Petit et al., 1999). The behaviour of the climate in tropical areas during these global climatic changes is highly debatable. In the region of Sao Gabriel da Cachoeira, palynologic data from Lagoa da Pata indicate that the vegetation retained forest tree elements, with replacement of elements associated with cold weather during the last glacial period (Colinvaux et al., 1996a) demonstrating that, despite changes in the pollen composition, there was no replacement of forest by cerrado (savanna type), as observed in Carajás during the last glacial period (Absy et al., 1991). New analyses of a sedimentary record from Lagoa da Pata (D'Apolito et al., 2013) present clear signals of structural changes in vegetation indicating that the area experienced a significantly drier climate during the LGM. These signals are in turn corroborated by geochemical data from Lagoa da Pata, which indicate hydrological changes during the last 40,000 years BP (Bush and Silman, 2004; Bush et al., 2004; Cordeiro et al., 2011).

Three phases of sedimentologic and organic evolution characteristics during the last 50,000 years BP (Fig. 7) have been identified in the LPT-V sediment core from Lagoa da Pata (Colinvaux et al., 1996a; Santos et al., 1999; Barbosa et al., 2004; Bush et al., 2004; Cordeiro et al., 2011; D'Apolito et al., 2013). From 50,000 to 25,000 cal years BP, an organic-rich clay with a high (14.4%) average TOC concentration indicates high lake level, with a large delivery of land-derived organic matter as evidenced by C/N weight ratio of approximately 29.0 (Meyers and Ishiwatary, 1993, Meyers, 2003). The low δ13C values can be explained by the input of isotopically light, carbon soil-derived to the lake, which can lead to local production of isotopically light algal organic matter (~−32‰). This episode of sedimentation was correlated with interpretations that the middle Pleniglacial represents a tropical palaeohydrological regime in the Rio Negro Basin with a higher discharge variability (Latrubesse and Franzinelli, 1998, 2005). Van Der Hammen and Hooghiemstra (2000) interpreted that the period from approximately 60,000 to 32,500 cal years BP is a period with a generally

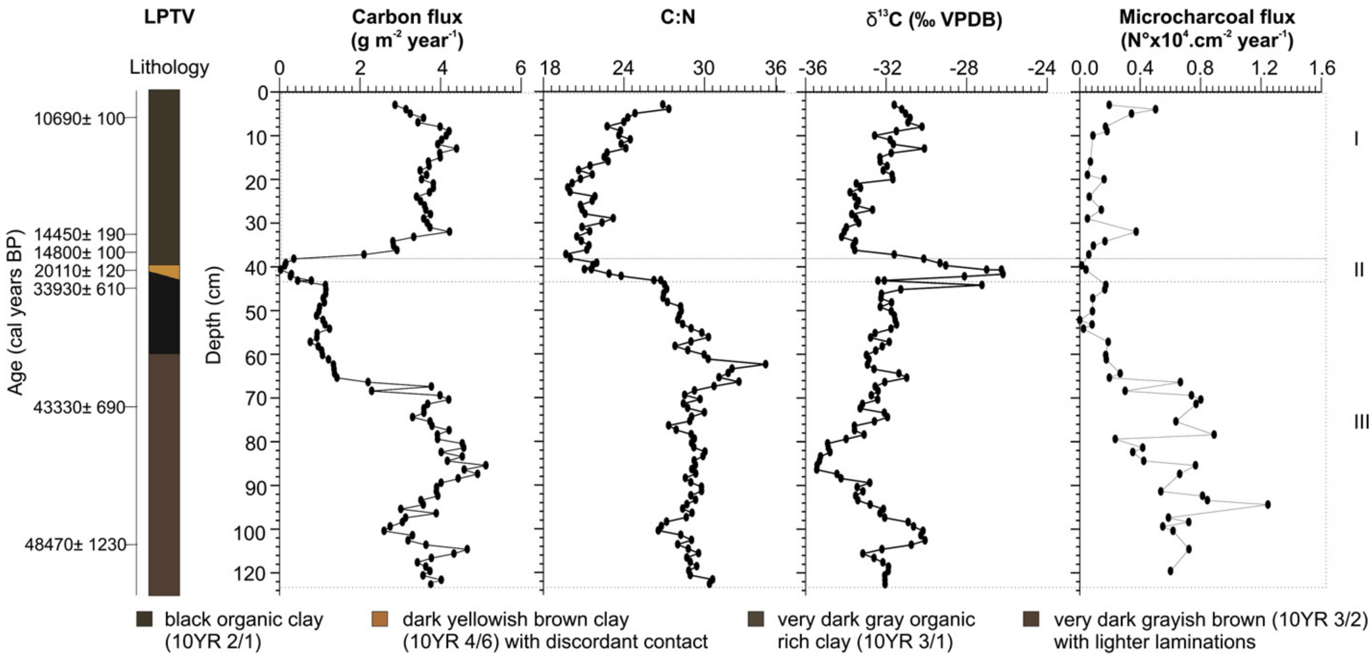

Fig. 7. Carbon accumulation rate, C/N ratio, $\delta^{13}C$‰ and microcharcoal accumulation rate in a in Lagoa da Pata, São Gabriel da Cahoeira (Amazonas State) during 50,000 cal AP until 10,000 cal AP, determined in LPTV core.

cold and wet climate condition corresponding to the high level of palaeoproductivity indicators observed in the LPT V core (Cordeiro et al., 2011). The charcoal accumulation during this period reached 4.72×10^3 particles cm^{-2} $years^{-1}$, with a maximum value of 1.25×10^4 particles cm^{-2} $years^{-1}$ at 46,900 cal years BP (Fig. 8).

A substantial decrease in the sedimentation rate was observed in the LPT V core between 31,000 cal BP and 17,000 cal years BP (Cordeiro et al., 2011) and is synchronous with a hiatus in sedimentation between 29,800 cal years BP and 19,200 cal years BP (Santos et al., 1999). The decrease in the sedimentation rate may be associated with a substantial decrease in the water level and a consequent decrease in lake productivity. TOC decreases ranging from 3.07% to 5.08%. There was a sharp decrease of the lacustrine productivity relative to the preceding phase, associated with a drop of the lake level. δ13C varied between −22.3‰ and −26.2‰. The presence of isotopically heavier carbon indicates the delivery of organic matter from C4 type species (Cordeiro et al.2011) leading a decreasing in biomass avaibility. The low water level is attributed to low rainfall, yet the lowest charcoal accumulation rate was observed. This rate reached 2.70×10^2 particles cm^{-2} $years^{-1}$ between 25,000 and 18,000 cal years BP, as recorded in LPT V core (Cordeiro et al., 2011). A low rate of evaporation most likely was due to low temperatures during the LGM, causing a low evaporation/precipitation ratio and a low rate of forest fire occurrences. During the late glacial and the Holocene periods, the core contains an organic-rich clay with

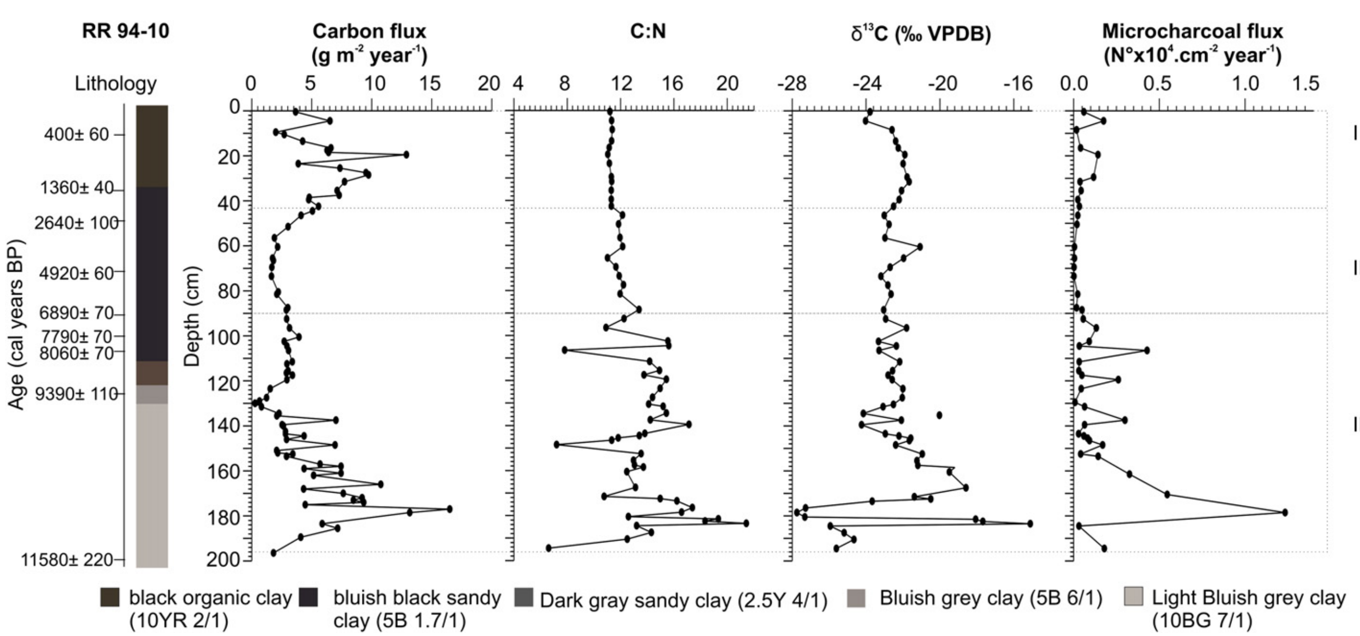

Fig. 8. Carbon accumulation rate, C/N ratio, $\delta^{13}C$‰ and microcharcoal accumulation rate in Lago Caracaranã (Normandia, RR), which has been surrounded by cerrado vegetation (savanna type) during the Holocene (ages calibrated interpolated), based on core RR 94-9.

high total organic carbon concentrations; the highest value in the top of the core reaches 23.2%. The C/N weight ratio in this phase is the maximum (33.4), indicating an important input of lignocellulosic material (Meyers and Ishiwatary, 1993; Meyers, 2003) that originated in the surrounding forested watershed. However, the top of the core displays a decrease in the C/N ratio, which dropped as low as 19.1, indicating an increase in planktonic activity. This change may be associated with a more humid palaeoclimate. Charcoal accumulation rate during this phase reached a relatively low average value of approximately 1.60×10^3 particles cm^{-2} $years^{-1}$ (Fig. 7).

4.7. Lago Caracaranã and the evolution of the cerrado/forest boundary in Roraima Lavrado during the Holocene

The TOC and micro-charcoal fluxes during the period of lake rise in the Lago Caracaranã record in the beginning of the Holocene correlate with the highest charcoal particle accumulation rates (Fig. 8), which reached 12,300 particles cm^{-2} $years^{-1}$ during the Early Holocene and Mid-Holocene. During the period from 11,300 to 5800 cal years BP, the main source of the carbon was the production of charcoal and fragments of debris fragments, most of which are larger than 100 μm. The high values of C/N ratio and δ13C indict that the organic matter is derived from plant fragments of C4 plants from cerrado vegetation. Charcoal deposition remained at high rates until 5800 cal years BP, with the highest rate of 4200 particles cm^{-2} $years^{-1}$ being reached at 7200 cal years BP. High charcoal accumulation rates during these phases were related to the dryness as attested by low water levels indicated by a low carbon accumulation rate. In contrast, during the phases corresponding to the transition from the middle to late Holocene (between 5800 and 2000 cal years BP) and the modern phase (the last 2000 years), the charcoal–TOC relationship was less clear, most likely due to human action. During the mid-Holocene, peaks of charcoal fluxes are attributed to small particles of charcoals. The primary charcoal peak was dated at between 10,200 cal years BP and 6800 cal years BP, with average values of approximately 1800 particles/cm^2/years, and a maximum of 12,300 particles cm^{-2} $years^{-1}$ at 9800 cal years BP. Between 6,800 cal years BP and 5,800 cal years BP, average values were approximately 360 particles cm^{-2} $years^{-1}$. The lowest values were found between 5800 and 2220 cal years BP, with an average values of 35 particles cm^{-2} $years^{-1}$. Thereafter, the charcoal fluxes increased, returning to values of approximately 400 particles/cm^2/years after 2200 cal years BP (Fig. 8).

5. Synthesis and discussion

Interpretations of biomass combustion require a comparison of the charcoal particle fluxes in various vegetation communities and at various time scales. The charcoal analyses may also have great importance in evaluating the impact of dry climates in various ecosystems. Charcoal accumulation in lakes commonly increases in a drier climate, but anthropogenic influences also increase the rate of charcoal deposition in the lake basins.

The distribution of charcoal particles in core At-1A previously published (Cordeiro et al., 2002) is correlated to the gross domestic product of Brazil, which decreased substantially in the early 1990s. Cores L-WNW-50 and L-LCEN-050 also reflect, such correlation with the economic recession of early 1991 (Cordeiro et al., 2002). Cattle ranching is very sensitive to economic changes, such as interest rates in financial markets, government subsidies on agriculture, inflation, and changes in the price of land (Fearnside, 1999). Climatic events such as El Ninõ can act synergistically with these economic factors (Kirchhoff and Escada, 1998). Core L-SSW-150 exhibits a peak just after the construction of a dam and reflects the beginning of the population growth described by Bosco-Santos et al. (2013). The gap observed between the cores is most likely due the local patterns of occupation. It is noteworthy that all of the cores displayed an increase in the charcoal particle flux after 1993/1997, which indicates an increase in slash-and-burn practices after the recovery in Brazilian economic activity.

In Lago Comprido, a floodplain lake of the Amazonas River system, the highest charcoal accumulation rate occurred after 2000 cal years BP, with a decrease after 350 cal years BP. Palaeoecological analyses of two lake districts (Bush et al., 2007) in central and western Amazonia reveal long histories of human occupation and land use that correlate with the record of Lago Comprido. The data from Gentry Lake (Peru, Gentry, 12°10′38.31″S; 69°05′51.54″W) provide direct evidence of cultivation, based on the presence of *Zea* pollen between 3700 and 500 cal years BP as well as by the presence of manioc from 2400 cal years BP. In the sediment record from Geral Lake in eastern Amazonia (1°38′48.85″S, 53°35′43.9″W), *Zea mays* pollen is also present and is accompanied by phytoliths (microscopic silica bodies that precipitate in and around plant cells) indicative of manioc between ca 4030 cal years BP and ca 850 cal years BP (Bush et al., 2007).

In the Humaitá region, the HUM97/5 core exhibits a high charcoal particle accumulation rate after 1400/1010 cal years BP with peaks at 340 cal years BP, suggesting forest fires resulting from synergetic interaction between climatic and anthropogenic impacts. A decrease in the charcoal accumulation rate centred at 1660 cal years BP corresponds to an increase in $\delta^{13}C_{org}$ and suggests a decrease in biomass availability due to expansion of grassland vegetation (Meyers, 2003). The minimum charcoal accumulation rate at 1400 cal years BP displays the same baseline in relation to the cerrado (savanna type vegetation) relative to Lago Caracaranã in Roraima, indicating the strong influence of the vegetation type and burnable biomass on the rate of charcoal accumulation. Whitlock et al. (2010), based on statistical modelling of global fire patterns, suggest that the distribution of fire is related to net primary productivity, because of the importance of burnable biomass. Increasing human population in the Amazon most likely made forest fires more common primarily after 3000 cal years BP, even taking into account that the climate during the late Holocene was wetter than during the mid/late Holocene as indicated by high lake levels in different neotropical sectors (Martins, 2012; Behling et al., 2001; Turcq et al., 2002a; Cordeiro et al., 2008; Moreira et al., 2012; Moreira et al., 2013a,b). Even assuming a higher lake level related to a wetter climate in the late Holocene, dry events related to human occupation in Amazonia are evidenced in the last 2000 years.

Meggers and Danon (1988) identified five successive complex archaeological phases on Marajó Island at the mouth of the Amazon River. Palynologic evidence of replacement of the forest (humid climate) by grasses and herbs (dry climate) in Marajó Island (Absy, 1982, 1985) and the presence of a cultural gap in the period between 2700 and 2000 years BP represented a direct evidence of the impact of climate change on the prehistoric inhabitants of the Amazon lowlands. Similarly, archaeological evidence in the Amazon displays gaps in the cultural sequences at approximately 1500 years BP, 1000 years BP, 700 years BP and 400 years BP (Meggers, 1994).

Palaeoecological data confirm that Amazonia was inhabited by indigenous peoples who practiced agriculture and developed urban centres, and these populations collapsed shortly after European contact (Bush and Silman, 2007). A review of archaeological data in different regions of Brazil suggests that during the mid-Holocene, vast areas of central Brazil ceased to be occupied by human groups, which did not happen in southern Brazil (Araujo et al., 2005). Two peaks of human occupation occurred in central Brazil, an early one around 8970 cal years BP and a later one just before European arrival, that were interspersed with low frequency of ages related to archaeological sites reaching a minimum at ca. 5710 cal years BP (Araujo et al., 2005). This phase is coincident with the intense forest fire occurrence recorded in the Carajás and Saci sites, located on broad leaf forests that border seasonal broadleaf forest regions that are transitional to the cerrados of central Brazil (see Fig. 1). These chronological correspondences show not only that humans had a significant impact on forest systems but also that the occurrence of severe dry events impacted the occurrence of vegetation fires and the populations and human settlements of the middle Holocene. After the dry phase of the middle Holocene, the population of the pre-Columbian people probably increased. Denevan (1992) points out that the forest composition had been modified, grasslands had been created, wild-life was disrupted, and erosion was severe in different places in South America including Amazonia. Brazilian Amazonia today has a population of 20.3 million of which only about 6 million live in rural areas and have significant impacts on land cover. Denevan (1992) estimates that in the low area of South America about 8.3 million inhabitants lived before AD 1496, although Meggers (1992) suggests the population may have reached 10 million people in the Amazon, which denotes the magnitude of the possible impacts of humans on the vegetation. Archaeological studies in the Xingu region have documented pronounced human-induced alteration of the forest cover, particularly those associated with large, dense, late-prehistoric settlements ca. 750 to 350 cal years BP (Heckenberger et al., 2003). However, McMichael et al. (2012a,b,c) used charcoal radiocarbon dating and concentrations in soil profiles to interpret that in western Amazonia the human influence on the ecosystems was sparse. Our data indicate that high charcoal accumulation rate occurred in the late Holocene in the Carajás Serra Sul/Serra Norte records and in the Lago Saci record when the lake levels were high and human populations probably was larger than in mid-Holocene, suggesting that the strong climatic control during mid-Holocene was suppressed by a large human influence during late Holocene. A marked reduction of biomass burning after ~500 years BP could be observed in records in the three Carajás lakes, Humaitá bog and Lago Comprido, with the Humaitá and Comprido Lake records being in agreement with the interpretation of the decrease in human influence due to a massive decrease in pre-Columbian human population (Nevle and Bird, 2008; Dull et al., 2010; Power et al., 2012). The rapid demographic collapse decreased by about 95% all estimated indigenous inhabitants (Dull et al., 2010) and consequently promoted a decrease in regional biomass burning as recorded by a charcoal accumulation rate index decrease after AD 1496 (Power et al., 2012). This decrease also is indicative of forest regrowth that promoted a decrease in CO_2 radiative forcing that has been linked to the occurrence of the Little Ice Age. (Nevle et al., 2011; Power et al., 2012).

In addition to the human influences on them, the absolute charcoal accumulation rate should be interpreted considering several geomorphological and microclimate factors and the vegetation types. Barbosa (2009) compared the historical wildfire susceptibility in the north and south sectors of the Carajas region, considering the charcoal accumulation rates and the current susceptibility to fires as based on the average climatic data for the 2007 dry season and local geomorphological features. Large differences between the charcoal accumulation rates of Serra Norte (Cordeiro et al., 2008, core CSN-93-3) and Serra Sul (Elias et al., 2001, core CSS-93-6 and Cordeiro, 2000, core CSS-93-2 (Fig. 5b)). These large differences, referred to as historic fire susceptibility, were comparable to the actual susceptibility that is based on algorithms that accounted for ground slope, precipitation, and vegetation among other factors (Barbosa, 2009). Despite significant differences in the charcoal accumulation rates of all of the South and North Carajás sectors, correspondingly large increases in the charcoal accumulation rates were observed between ca. 8000 cal years BP and 4000 cal years BP and between 1200 cal years BP and 400 cal years BP (Fig. 5b).

A charcoal accumulation rate increase for the Lago Saci was primarily observed from the early until the middle Holocene when the lake level was low (Fig. 3). Increases in the lake level during the late Holocene (Martins, 2012) are associated with the highest charcoal accumulation rate in the record, as is the case for core CSS-93-2 from Serra Sul of Carajás, (Fig. 5b). This feature likely reflects the synergism between human activities and dry events in the late-Holocene at these two locations.

The lowest charcoal accumulation rates among the seven locations in this study are observed in the Lagoa da Pata record (Fig. 7) and the Caracaranã record (Fig. 8). The low values at Lagoa da Pata cover the time span between 50,000 and 10,000 cal years BP and probably reflect the combination of low human impact over this time and an extremely wet regime (3000 mm/years) that made a local ecosystem that was not very susceptible to forest fires. The lowest charcoal accumulation rate in Lagoa da Pata was during the LGM when moisture delivery was the lowest and possibly led to a decrease in forest biomass and fuel availability. Changes in fire regime during the LGM (Daniau et al., 2010) have been related to decreasing productivity that is principally attributed to low temperatures (Colinvaux et al., 1996b) and to a lesser extent to drier conditions (Daniau et al., 2012). Temperature increases related to the Holocene Thermal Maximum are characterised by relatively warm climates between 11,000 and 5000 years BP as indicated by numerous proxy records (Renssen et al., 2012). The temperature increases during early to middle Holocene are associated with major changes in the precipitation/evaporation balance that are considered responsible for regional decrease in hydrological balance recorded by low lake levels during the mid-Holocene in Amazonia (Baker et al., 2001; Cordeiro et al., 2008; Moreira et al., 2012, 2013a,b; Turcq et al., 2002a,b) and an increase in fire occurrences. Melo and Marengo (2008) reconstructed high temperature and low precipitation in Amazonia sectors based on model simulations of mid-Holocene conditions. This situation would be caused mainly by the reduced intensity of northwesterly trade winds north of 20°S, resulting in a northward positioning of ITCZ and weakening low level convergence in Amazonia.

Comparison between changes in the charcoal deposition rate related to land use change and those related to palaeoclimatic events indicates that the recent human impacts to the forest ecosystems recorded at the Alta Floresta sites (Fig. 9) are unprecedented. This comparison suggests that the loss of biomass in recently fragmented landscapes in the Amazonian landscapes may indeed be a significant source of greenhouse gas emissions as postulated by Laurance et al. (1997). In addition, the combination of the human ignition factor and drier climate may have caused wildfires to spread to large areas. Power et al. (2008) interpreted charcoal content variations in terms of changes in biomass burning and concluded that climatically determined changes in fire conditions may have had significant impacts on the global carbon budget through time. Increases in wildfire susceptibility as a consequence of combined human activity and drought may increase the likelihood that small fires initiated by humans can run out of control and become large wildfires (Bush et al., 2008). Dry climates, increased seasonality and human-induced factors may have led to significant changes in global carbon biogeochemistry, particularly in relation to the exchange of carbon between the terrestrial biosphere and the atmosphere principally during the mid-Holocene (Indermühle et al., 1999; Carcaillet et al., 2002; Rudimann, 2003).

The timing of major fires coincides with the early to mid-Holocene (ca 8000–4000 years cal BP) dry climate phase in Amazonia (Irion et al., 2006; Cordeiro et al., 2008; Mayle and Power, 2008). An increase in CO_2 recorded at the Taylor Dome Station (Indermühle et al., 1999) beginning at 8000 cal years BP corresponds in time with the occurrence of forest fires of the early to mid-Holocene dry phase that produced strong peaks in charcoal-related carbon fluxes to the atmosphere. The magnitude and frequency of biomass burn events in Amazonia may have affected the carbon cycle through CO_2 emissions to the atmospheric or oceanic compartments. These events have increased the concentration of greenhouse gases in the atmosphere and thus may have contributed to the warming experienced since the start of current interglacial (Indermühle et al., 1999; Carcaillet et al., 2002; Ruddiman, 2003). The discrepancy in the charcoal accumulation rate may be attributed to variations in biomass availability in these ecosystems and intense climatic change.

Large discrepancies in the flux values (Fig. 9) and palaeofire intensity become apparent when the different areas are compared.

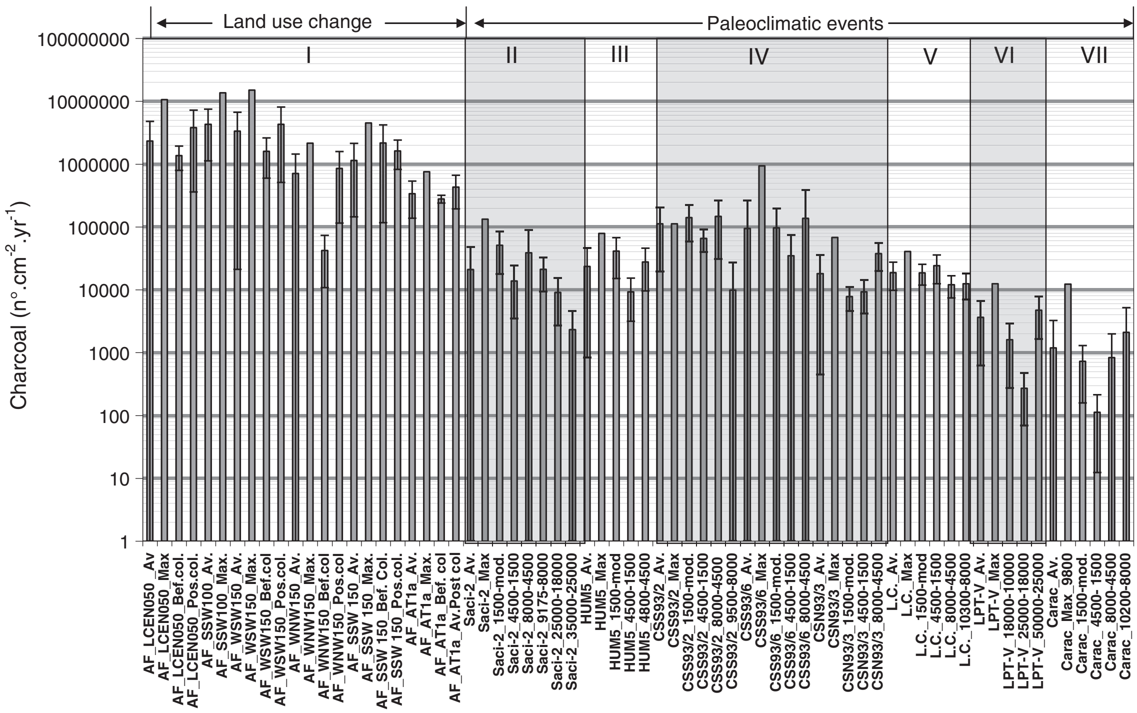

Fig. 9. Charcoal accumulation rates in different records and time scale: (I) Alta Floresta (Mato Grosso State) AF_LCEN050 core, AF_SSW100 core, AF_WSW150, AF_WNW150 core, AF_SSW150 core (Bosco-Santos et al., 2013), AT1a core (Cordeiro et al., 2002). Av = Average values during the entire record, Max. = Maximum value, Befcol. = Before colonisation, Pos.col = After colonisation II) Lago Saci (Pará State), Saci2 core between 35,000 and 25,000, 25,000 and 18,000, 9175 and 8000, 8000 and 4500, 4500 and 1500, 1500-modern cal BP; (III) Humaitá region (Amazonas State) HUM5_ core in between 4800 and 4500 cal BP, 4500 and 1500 cal BP, 1500-modern; IV) Carajás site (Pará State), CSS93/2 between 9500 and 8000, 8000 and 4500, 4500 and 1500, 1500-modern cal BP, CSS93/6 (Elias et al., 2001) between 8000 and 4500, 4500 and 1500, 1500-modern cal BP core, CSN93/3 (Cordeiro et al., 2008) between 7400 and 4500, 4500 and 1500, 1500-modern cal BP; CSS93/2 between 9500 and 8000, 8000 and 4500, 4500 and 1500, 1500-modern cal BP; (V) Monte Alegre (PA) region, LC_ core in Lago Comprido between 10,300 and 8000 cal BP, 8000 and 4500 cal BP, 4500 and 1500 cal BP, 1500-modern cal BP; (VI) Morro dos Seis Lagos, São Gabriel da Cachoeira (Amazonas State), LPT-V core in Lagoa da Pata between 50,000 and 25,000, 25,000 and 18,000 (LGM), 18,000 and 10,000 (Cordeiro et al., 2011); and (VII) Caracaranã region, Carac_core in Lago Caracaranã (Roraima State) between 10,200 and 8000, 8000 and 4500, 4500 and 1500, 1500-modern cal BP (Simões Filho, 2000).

These discrepancies can be attributed to differences in the biomass available in these different ecosystems, the intensity of their water deficits, the extent of human presence, and considerable changes in seasonality due to changes in insolation. As observed and discussed in the Carajás region, some of the differences can be traced to such geomorphological features as land slope, total area of the lake basin, and the lake basin/lake area relation.

The highest charcoal accumulation rate was observed in an area of intense land use change in the Alta Floresta region. Changes in the charcoal accumulation rate in these records are linked to the economic fluctuations (FGV, 2000). The highest charcoal flux values were observed during the period of intense land use change from forest to cattle ranching and agriculture and were approximately 5 times higher than the highest values obtained in the palaeoenvironmental records in Carajás Serra Sul (CSS93/2) in sediments that represent the mid-Holocene.

6. Conclusions and implications

The Amazon lakes of today are products of environmental development over different time scales and under different conditions of environmental fluctuations. Lake hydrological dynamics were once governed only by palaeoclimatic changes but today are controlled by a combination of human activities and climate. The magnitudes of such events are recorded in the sediment cores, with charcoal particles an important marker of these changes.

Changes in charcoal accumulation rates reveal an unprecedented extent of changes in human disturbances and land use. The disturbance events related to land use changes far outweigh the environmental changes caused by natural climatic events, especially markedly for the late Holocene period when forest vegetation reached a peak in biomass and the presence of humans was first recorded.

When comparing changes in the charcoal accumulation rates of lake sediment records from various nearby sectors (e.g., Carajás Serra Sul and Serra Norte), the same increasing trends during the middle and late Holocene were observed. However, in the Serra Norte, Lake N4 exhibits charcoal accumulation rates much lower than those of the Serra Sul lakes. These results were congruent with current wildfire susceptibility data based on climatic, vegetation and geomorphological parameters (Barbosa, 2009; Barbosa et al., 2010) and indicate that the charcoal accumulation rates depend not only on climatic factors but also on associated geomorphologic, vegetation and human factors.

Lower charcoal accumulation rates during the last 50,000 years were produced in modern high rainfall environments, as observed in Lagoa da Pata, because relatively drier climatic phases do not necessarily make the environment more susceptible to the occurrence of wildfires. Low accumulation rates were observed in the area of a modern-day relatively dry climate with cerrado vegetation in Roraima, where there is a low amount of biomass and a consequent low rate of charcoal particle generation. These features were also observed for the climatic phases of the Late Pleistocene that led to the development of the cerrado, as observed in southern Pará State (Lago Saci, Martins, 2012).

The timing of fires correlated well with the mid-Holocene dry climate phase in Brazil. Discrepancies in the flux values may be attributed to variations of biomass availability in these ecosystems and to palaeofire intensity. Justino et al. (2010) points out by using an index used to estimate wild-land fire severity (Haines index) that a marked drop in precipitation during the mid-Holocene increased the flammability in South America. These events may be related to changes in the high-resolution record of CO_2 in ice cores from the last 11,000 years

(Indermühle et al., 1999). These records indicate an increase in CO_2 concentration of 25 p.p.m.v. that occurred between 7000 and 1000 years BP. Anomalies of 5 ppm in the CO_2 concentration in the atmosphere identified at the Taylor Dome station may similarly be related to the high variability in forest fire occurrence in the Amazon region recorded by the high charcoal accumulation rates that can be associated principally with human activity during the late Holocene, especially considering from higher lake levels that indicate a wetter climate compared to the mid Holocene.

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