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Late Holocene paleoenvironments of the floodplain of the Solimões River, Central Amazonia, based on the palynological record of Lake Cabaliana

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ABSTRACT

The core PD-67 of 160 cm depth was collected from the delta of Lake Cabaliana situated on the Solimões River. Seventeen samples were removed for palynological and sedimentological analysis and three for radiocarbon analysis. Two dry periods, both in the Late Holocene, were observed (2800-2550 cal yr BP, 1450-550 cal yr BP) separated by a wetter phase (2550-1450 cal yr BP). In 2800-2550 cal yr BP, *varzea* forests of *Alchornea*, *Symmeria*, *Cecropia, Alternanthera* and Asteraceae were predominant. Beginning in 2,550-1450 cal yr BP, the varzea was characterized by pioneer elements, such as *Cassia*, *Laetia*, *Mabea, Symmeria and Cecropia,* and by the expansion of Poaceae, Cyperaceae, *Sagittaria*, *Montrichardia* and Asteraceae. In 1450-550 cal yr BP the succession of varzea continued with *Pseudobombax, Laetia, Luehea/Lueheopsis* and *Ryanaea* increasing simultaneously with the *terra firme* vegetation of Rutaceae, Sapotaceae, *Styrax, Scleronema*, *Anthurium, Araceae*, pteridophytes and *Pariana*. The successional dynamics at Lake Cabaliana indicated that the local *varzea* had become established recently, and is composed of a mosaic of different successional stages of vegetation influenced mainly by flood pulse and variation in rainfall. It is therefore possible to propose that the recent climate history of Central Amazonia reflects changes in rainfall patterns in the basin.

Keywords: Amazon, pollen, Quaternary, rainfall, *terra firme* forest.

Introduction

In South America, the late and middle Holocene was marked by a rise in sea level and the advancement of the Intertropical Convergence Zone (ITCZ). The increase in humidity over the last 4000 years is considered to be a result of the southward advance of the ITCZ, which distributes rainfall in tropical South America (Marchant & Hooghiemstra 2004).

In the Amazon ecosystem, responses to climate were not homogeneous due to the vast extension of the forest (latitudinal variation) and its immense heterogeneity. Amazonian plant communities are among the most diverse in the world, with more than 80,000 *taxa* of vascular plants having been described, and occurring in densities of more than 300 species per hectare (Gentry 1993). In the Amazon rainforest - savannah ecotone, the forest replaced cerrado over an extension of about 300 km (Mayle *et al*. 2000; Burbridge *et al*. 2004), in the last 2000 years, which is considered the largest southern amplitude that the Amazon forest reached during the Quaternary.

To the north, in the savanna of the Llanos Orientales (Colombia), increased rainfall caused the development

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of gallery forests during the same period (Behling & Hooghiemstra 1998; Berrío *et al*. 2002). Dry periods, as a result of decreased rainfall about 4,000, 2,100 and 700 years BP, were reported for the Central Amazon by Absy (1979). In Lake Caju, near Manaus (Amazonas), variation in the composition of the *varzea* forest have been documented. A dry phase was recorded 2150 years BP, which was also detected in Costa da Terra Nova in the Solimões River floodplain. In Lake Tapajós, in the eastern Amazon, Irion *et al*. (2006) reported changes in vegetation between 5,500 and 4,200 years BP. The pollen record indicates that the area around the lake was possibly forested during the Holocene, however, sedimentological analysis and the abundance of *Poaceae* and *Cecropia* suggest an increase in human activity in the region.

In this context, the analysis of river sediments has proven to be interesting, because rivers respond rapidly to changes at mid- and small scales, providing information about climate fluctuations (Thomas & Thorp 1995). Depositional processes are influenced by changes in water level caused by fluctuations in sea level and by seasonal changes in precipitation. (Marengo 1992; Irion *et al*. 1997; Junk 1997; Marengo *et al*. 1998; Schongart *et al*. 2004). A pollen record from a Amazonian palm swamp in Peru, combined with sedimentary evidence, suggested that the dominant control of ecosystem functioning and development is the flood regime (Roucoux *et al*. 2013).

Lake Cabaliana was chosen for investigation because it is one of the largest lakes in the Central Amazon. It is located on the alluvial plain of the Solimões River (left bank), and has been poorly studied (Sá & Absy 2011). Therefore, the results of the present paper will allow a comparison with previous palynological studies in the Central Amazon and will contribute to a better understanding of the succession of vegetation and its relationship to the sedimentological features and precipitation during the Holocene of the region.

Materials and methods

Study Area

Structural and geomorphological aspects

The Solimões River is distinctive with its channel and lakes conforming to the floodplain, which has been related, directly or indirectly, to structural control (Latrubesse & Franzinelli 2002; Bezerra unpubl. res.). Inclinations of tectonic blocks (Tricart 1977), fracture patterns (Sternberg 1950) and neotectonic lineaments (Latrubesse & Franzinelli 2002) have influenced the development of this river. Lake Cabaliana (3° 17' 35.62"S and 60° 48' 18.71"W) is located west of Manacapuru, 78 km from Manaus, in the area of tectonic structure called "rhomb transtensive Manacapuru." This structure is defined as a basin of withdrawal or pull-apart structure, being defined by bundles of transcurrent and normal faults (Latrubesse & Franzinelli 2002; Bezerra unpubl. res.). In the northern portion of this structure, normal faults gave rise to Lake Cabaliana (Bezerra unpubl. res.).

Lake Cabaliana is bordered to the north and to the east by upland areas that are 60 m to 97 m above sea level and are not subject to annual flooding of the Solimões River. The uplands are composed of sedimentary rocks (conglomerates, sandstones and mudstones) from the Alter do Chão and Novo Remanso Formations that are Cretaceous and Miocene, respectively (Soares *et al*. 2010). Lake Cabaliana is a large, complex, permanent floodplain/lower fluvial terrace lake with a mean water elevation of 15 m a.s.l. It is ~32km in length and ~8 km in width above sea level and is composed of sedimentary deposits from the alluvial plain of the Solimões River. The lake developed on an older scroll-dominated plain of late Pleistocene age (Latrubesse & Franzinelli 2002). Morphologically, the lake is composed of several geomorphic elements that combine, in a single system, different lake categories and styles such as abandoned channels, scrolls and levee-delta lakes (Latrubesse *et al*. 2012). The drainage of these lakes is crucially dependent on local precipitation, the flood pulse of the main Solimões River channel and inputs from smaller tributaries draining the surrounding terrain (Melack 1984, Sperling 1999). Levees and delta lakes are characteristic of large, permanently flooded areas in the floodplain, and rounded lakes can develop by the coalescence of levees in the floodplain (Latrubesse & Franzinelli 2002; Latrubesse *et al*. 2012). Deltas at Lake Cabaliana are located west and south, and they extend for 10 km. They are generally straight to slightly curved and have few branches (Feitosa & Soares unpubl. res., RADAMBRASIL 1978). The most significant branch developed in the discharge of the Paranã Piranha River (Figs. 1, 2). The deltaic deposits are composed of yellowish-brown to medium-grey-colored sand and mud (silt and clay), which compose the floodplain, marginal levees, and delta front (Feitosa & Soares unpubl. res.). The delta front usually remains submerged and is composed of lobed bodies that contain decimeter to centimeter-thick rhythmic intercalations of sand and mud layers (silt and clay). The layers are gently sloping (about 17°) toward the center of the lake (Feitosa & Soares unpubl. res.) (Fig. 2). The sand layers are massive, yellowish in color, have a fine to very fine particle size and contain little silt and associated clay (Fig. 3). The layers of mud (silt and clay) have a grey to brown colour with irregular concentrations of organic material (black) and iron (red) with incipient inclined lamination (Feitosa & Soares unpubl. res.).

Hydrology

Central Amazonia is characterized by a warm and humid tropical climate (RADAMBRASIL 1978) and has an average rainfall of 2,100 mm yr^{-1} (Fisch *et al*. 1998). The thermal

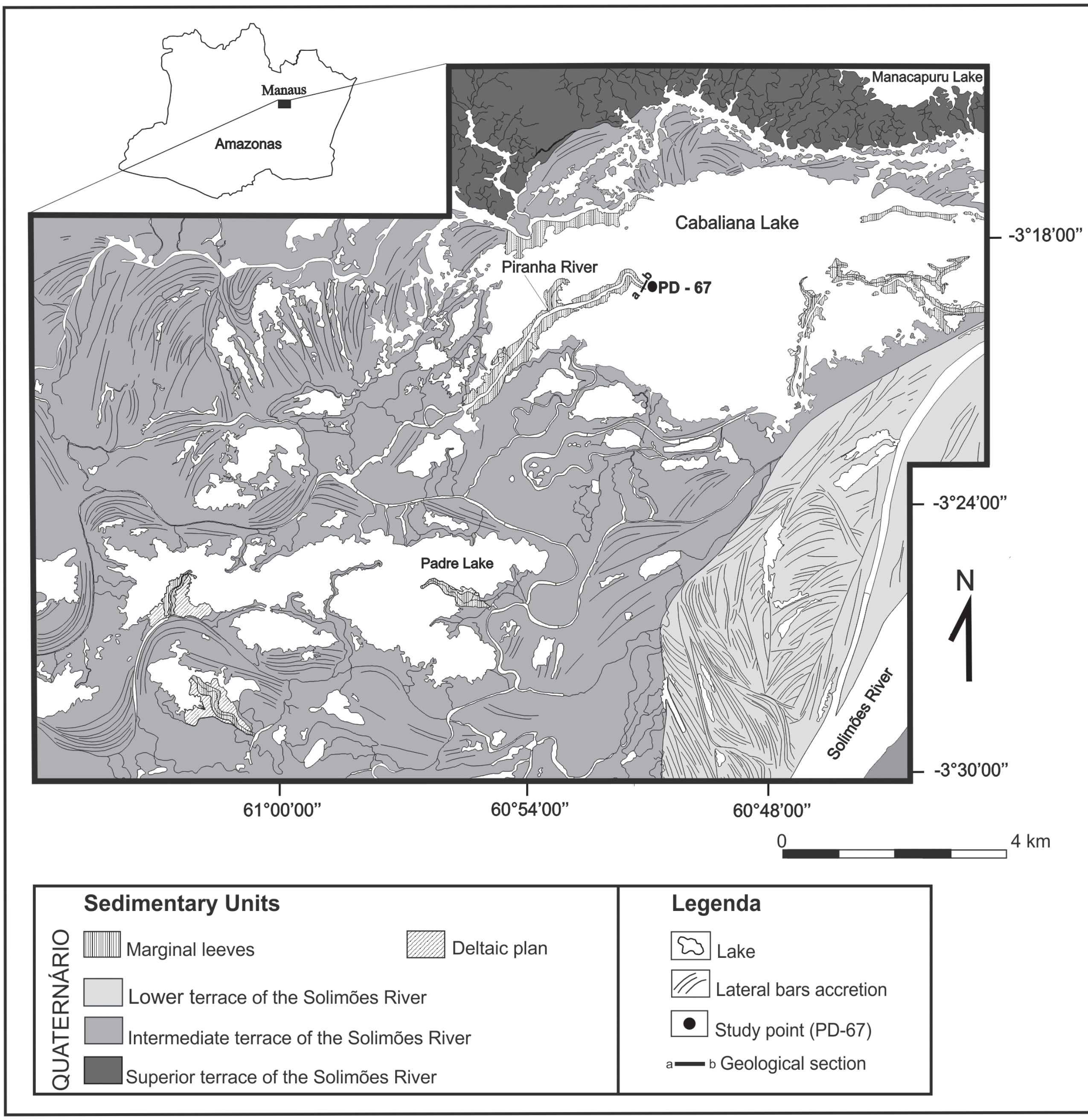

Figure 1. Geological map of the Solimões River floodplain, Central Amazon. The map was adapted from Feitosa & Soares (unpubl. res.).

amplitude is small, ranging from 27.6° C to 27.2° C in August to November and from 25.9 ° C to 26.1 ° C in January to April. The rainy months are from December to April, while the dry season is from June to November. The frequency of rainfall influences the level of rivers and channels, and produces fluctuations in water levels of about 10 m (Irion *et al*. 1997). Variation in water flow of the rivers follows the fluctuation between wet and dry seasons so that the water level of the channel develops a monomodal curve called the flood pulse (Junk 1989; 1997).

Vegetation

The vegetation surrounding Lake Cabaliana is mainly composed of *varzea* forest but is bounded by *terra firme* forest to the north and northwest (about 2.5 km). There have been no floristic studies for the area, and so we used references about floristic composition and vegetation structure for other areas in Central Amazonia (cited below). Taxonomic units were grouped according to their ecological affinities, habit, or habitat based on floristic studies: Gentry (1993);

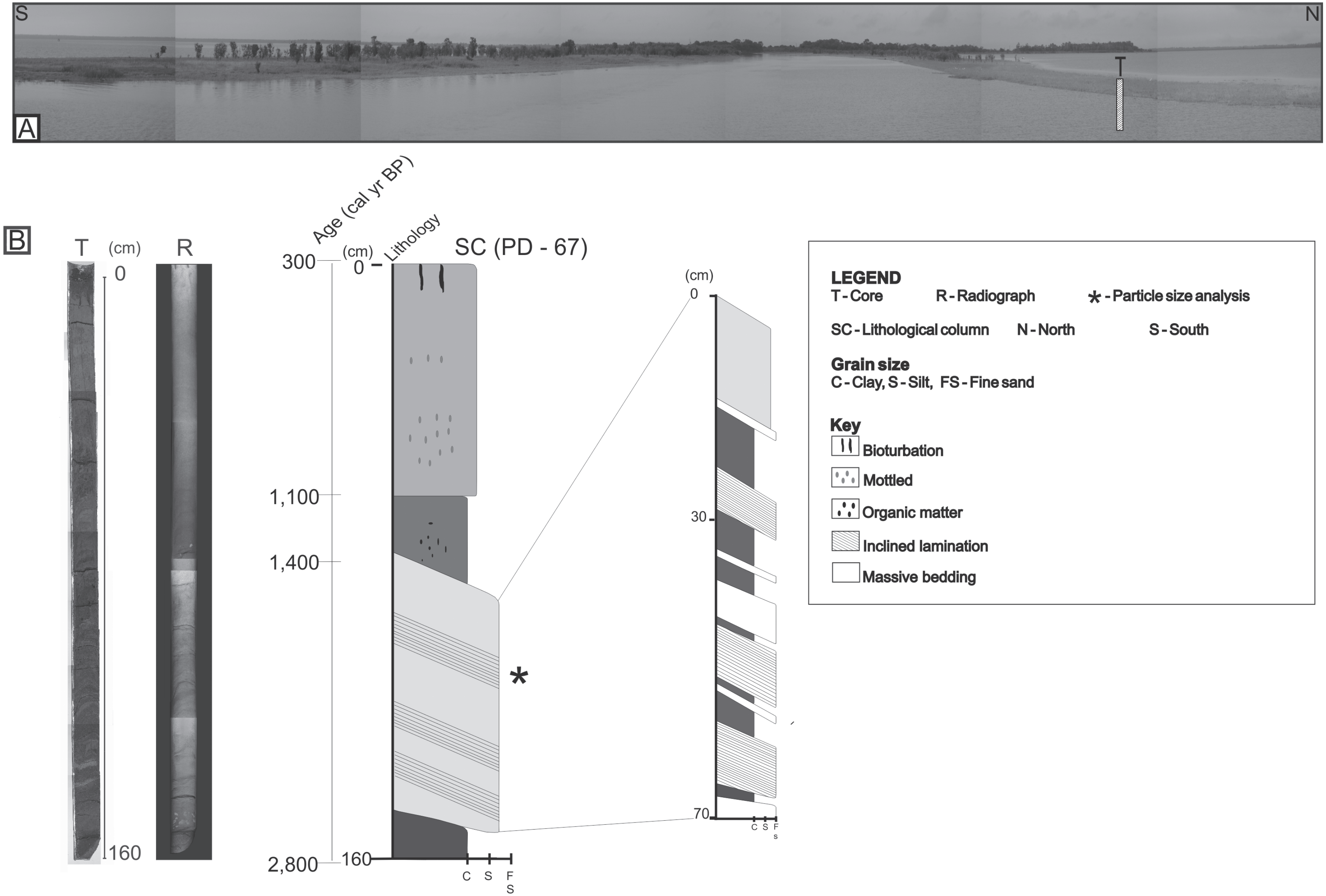

Figure 2. (A) Discharge of the Lake Cabaliana main delta. (B) Photography, radiography, and columnar section of the PD-67 drill core. Adapted from Feitosa & Soares (unpubl. res.).

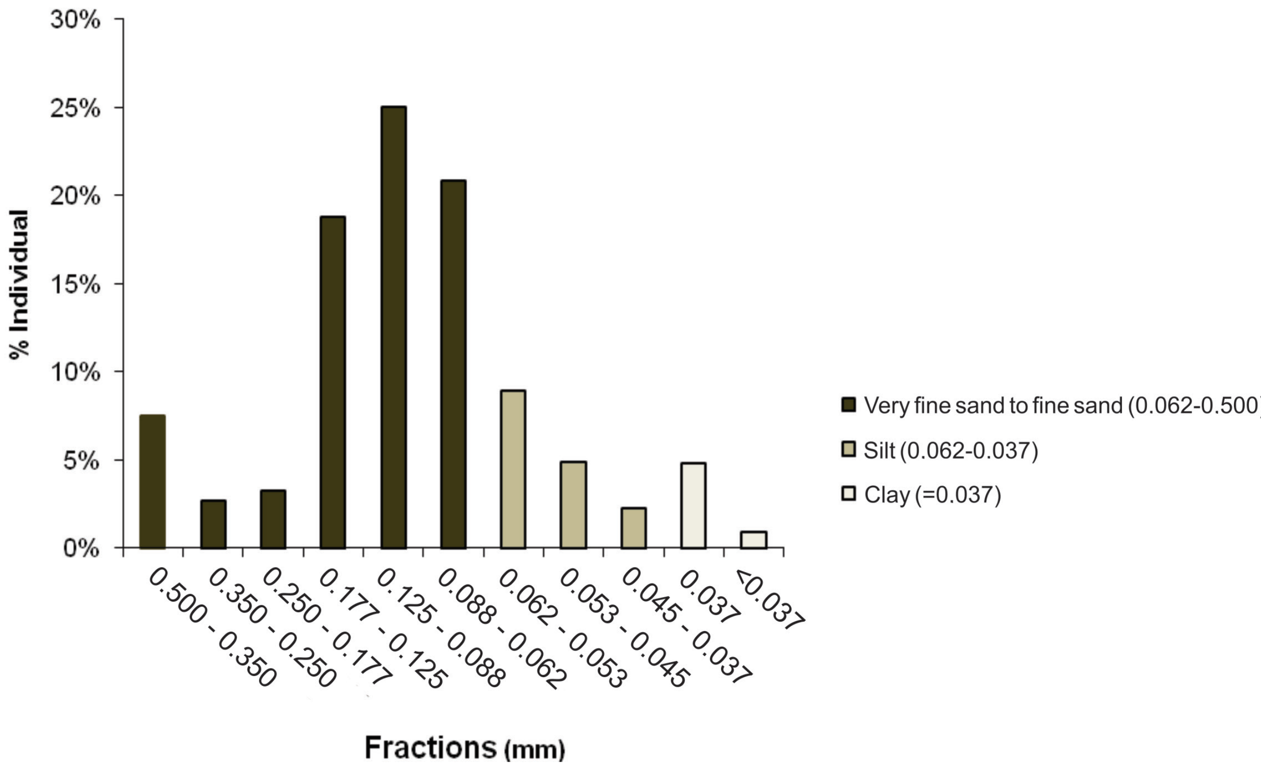

Figure 3. Granulometric analysis of PD-67.

Prance *et al*. (1976); RADAMBRASIL (1978); Rankin-de-Merona *et al*. (1992); Ribeiro *et al*. (1999); Souza & Lorenzi (2005); Oliveira & Amaral (2005) and Oliveira *et al*. (2008); or ecological descriptions: Gosling (2005); Marchant *et al*. (2002); Parolin *et al*. (2002; 2004); Wittmann *et al*. (2002; 2004; 2006); Worbes *et al*. (1992) and Worbes (1997) (Tab. 1). We chose to use the ecological terms *varzea* and *terra firme* (Prance 1979; Pires & Prance 1985) to designate floodplain forest and upland forest, respectively.

Field sampling and analysis

The drilling of PD-67 was conducted in the southwestern part of Lake Cabaliana, which is in the deltaic front of Paraná do Piranha Lake, using a Vibracore core drill. A 160 cm-long core was collected from the delta of Lake Cabaliana on the alluvial plain of the Solimões River, Central Amazon (Fig. 2). In order to support sedimentological descriptions, mud samples (silt and clay) and sand core samples were collected for particle size analysis using mechanical sieving with various sized sieves (between 0.037 mm and 0.250 mm). Particle size distributions were represented by simple frequency histograms in order to analyze the proportion of clay, silt and sand in the studied samples.

For pollen analysis, a total of 17 samples of 4 g of sediment were extracted systematically every 10 cm. The samples were pre-treated with potassium hydroxide and then acetolysed (Erdtman 1960; Faegri & Iversen 1989). The palynomorphs were separated using the gravity technique (bromoform solution/ethanol: 2:1). Three tablets of *Lycopodium clavatum* were included in each sample at the beginning of the preparation (Stockmarr 1971). The palynomorphs were arranged in glycerine gel, sealed with paraffin, quantified using an optical microscope of 400x and 1000x magnification and identified by comparison with reference slides from the Palynology Laboratory of the National Institute of Amazonian Research and by consulting additional resources: Absy (1975; 1982); Colinvaux *et al*. (1999); Roubik & Moreno (1991); Salgado-Labouriau (1973). Counts included at least 300 pollen grains of terrestrial taxa with 100 spores of *L. clavatum* in each sample. Hydrophytes, algae, fungi, and pteridophyte spores were counted in parallel. Three subsamples were used for dating (Tab. 2) by *Accelerator Mass Spectrometry* (AMS) by the *Beta Analytic Radiocarbon Dating Laboratory* (U.S.). The 14C dating of samples Beta- 271674, 271675 and 271676 were calibrated using IntCal04 (Radiocarbon 2004) with the references to the mathematics of Talma & Vogel (1993). Data are presented in calibrated years (cal yr) BP and were interpolated and extrapolated for the profile using *TiliaGraphView*.

Statistical methods

Data were statistically tabulated in percentage diagrams and concentration rate was processed using *Tilia* software

Table 1. Palynomorphs used in the PD-67 profile of Lake Cabaliana.

Vegetation Formation/ Occurrence		Palynomorphs
Aquatic		*Sagittaria*, Cyperaceae, Poaceae, Pontederiaceae, *Nymphaea*, algae.
***Terra firme* forest**		*Anthurium*, Araceae, *Bactris*, *Pariana*, Poaceae, *Arrabidaea*, *Mabea*, *Scleronema*, *Protium*, *Cassia*, *Cecropia*, *Clusia*, *Symphonia*, *Vismia*, *Doliocarpus*, Fabaceae, *Byrsonima*, Melastomataceae, Combretaceae, Moraceae, *Piper*, Rubiaceae type II, Rutaceae, *Cupania*, *Neoxythece*, Sapotaceae, *Simaba*, *Desmodium*, *Styrax*, Urticaceae, *Bactris*, Asteraceae, pteridophytes, fungi.
***Varzea* forest**	**High varzea forest**	*Alternanthera*, Poaceae, *Alchornea*, *Sapium*, *Ryanaea*, Rubiaceae II, Urticaceae, Malvaceae, *Hyeronima*, *Holopixidium*, *Sapindaceae*, pteridophytes, fungi.
	Low varzea forest	*Montrichardia*, Cyperaceae, Poaceae, *Arrabidaea*, *Cecropia*, *Symmeria*, *Ludwigia*, Rubiaceae type II, Myrtaceae, *Laetia*, *Pseudobombax*, *Tabebuia*, *Alchornea*, *Luehea*, *Gustavia*, *Cassia*, *Alternanther*, pteridophytes, fungi.
Moor		*Bactris*, *Byrsonima*, pteridophytes, fungi.
Montana forest		*Weinmannia*, pteridophytes, fungi.

and plotted with *TiliaGraphView*. The diagrammed taxa were selected by their frequency, which was at least three grains (1% of total terrestrial taxa) per sample. The diagrams were sorted from highest to lowest by the total frequency of taxa while respecting the classification already described. The dendrogram analysis of hierarchical elements was done with the software CONISS (Grimm 1987; 1992). Pollen zones were defined according to the observed similarity in the dendrogram coupled with the frequency of each taxon. To estimate the abundance of terrestrial taxa, we used PAST (Hammer *et al*. 2005) to obtain a rarefaction curve (sampling effort), and then a Chi-square test ($\chi2$) with $P < 0.01$ using Excel for Windows software.

Results

Radiocarbon dating with AMS detected Late Holocene ages (Tab. 2). Four palynological zones were established and comprise the palynomorphs plotted according to the cluster analysis (CONISS) (Fig. 4). Zone III was divided into two subzones, Zone IIIa and Zone IIIb, because the palynological assemblages were very distinct and there was a sudden drop in concentration.

Zone I (160-145 cm: 2,800-2,550 cal yr BP. Grayish orange clay)

This zone is marked by clay with massive bedding characterized by decantation of fine particles in suspension: silt and clay (Fig. 2). In this zone, *varzea* taxa represented about 60% of the total terrestrial pollen, of which *Alchornea*, *Symmeria* and *Cecropia* represented approximately 40%. *Alternanthera*, Myrtaceae and *Tabebuia* (low *varzea* forest) accounted for 20%, and *Sapium* (high *varzea* forest) did not exceed 5%. *Terra firme* forest taxa represented 15%, and reduce in 2550 yr cal BP. Rutaceae, *Scleronema*, *Piper*, *Protium*, and *Bactris* represent 2% of all the terrestrial elements. *Varzea* and *terra firme* forest taxa reached 25% of the sum. Poaceae Moraceae/Urticaceae and Melastomataceae/Combretaceae were the most representative taxa of this zone. Aquatic plant pollen, algae and spores increased to 20% in 2550 yr cal BP, while fungi decreased from 40% to 20%. The total concentration in this zone was very low (Fig. 4).

Zone II (145-90 cm: 2,550-1,450 cal yr BP. Fine sand and mud (silty-clay))

In this zone there is the intercalation of thin laminae of very fine to fine sand and mud (silt and clay) (Fig. 2) indicative of higher and lower flow of the Paraná do Piranha, respectively. These changes may be associated with the hydrological cycle of the Solimões River. The sandy layers are reflexes of the major flow channel and, consequently, greater transport and deposition of sand particles, while the intercalation of mud reflects a phase of lower flow in the channel. The representation of *varzea* forest is predominant. At the beginning of the zone (2,550-2,350 cal yr BP), *varzea* forest taxa *Symmeria* and *Cecropia* have constant percentages (10% each) and *Alchornea* pollen decreased sharply (5%). *Sapium* and Myrtaceae remain at low frequencies (less than 5%). *Alternanthera* and *Montrichardia* maintain 15% and 5% of the pollen sum, respectively. Other *varzea* forest taxa are not represented in this interval (Fig. 4). Taxa of *terra firme* forest increased since the end of the subjacent zone, totaling about 12% of the pollen sum, and remaining constant up to 2250 cal yr BP. From 2100 cal yr BP, the *terra firme* forest represents 20% of the total, but this percentage declines to about 15%, and then remains constant until the end of this zone. Among the pollen of the *terra firme* forest in this interval, there is a predominance of herbaceous plants such as Asteraceae and *Senecio* type, Araceae and genus *Anthurium* (about 15% of total). *Varzea* and *terra firme* forest maintain a percentage of 25% at the beginning of this interval, reaching 40% at 1,650 cal yr BP. The pollen of Moraceae/Urticaceae stood out because they reached 10% of the total of the terrestrial components. Poaceae pollen increases to 35% in

Table 2. AMS radiocarbon dates for sedimentary profile (PD -67) of Lake Cabaliana.

Sample depth (cm)	Types of sediments	Laboratory code	AMS ^{14}C yr BP (Conventional ages)	Calibrated yr BP (1σ)
28 – 34	Gray clay with charcoal	Beta – 271675	830 ± 40	800 to 680
84 – 90	Gray clay with charcoal	Beta – 271676	1,570 ± 40	1,540 to 1,370
145 – 151	Gray clay with charcoal	Beta – 271674	2,570 ± 40	2,760 to 2,700 2,640 to 2,610 2,590 to 2,540

1750 cal yr BP and decreases to less than 10% by the end of the zone. The total sum of aquatic plants (20%) corresponds to the sum of Cyperaceae and *Sagittaria*. The percentage of algae and fungi oscillate, decreasing in frequency to less than 2% in 2350 and 2050 cal yr BP, respectively. At the border with the upper zone, algae and fungi are more frequent, with 20% and 40%, respectively. Pteridophytes are less frequent in this interval, being more represented in 1750 cal yr BP (5%) and in subsequent zones. As in the previous zone, the rates of total concentration and total accumulation remained low (Fig. 4).

Zone IIIa (90 - 49cm; 1,450 - 950 cal yr BP. Grayish clay and grayish silty clay)

Between 1,450 and 1,100 cal yr BP (85-62 cm), gray clay sediments predominate, which indicate a low rate of sedimentation (Fig. 2). The *varzea* forest remains prevalent, constituting about 50% of the vegetation, whereas the pollen frequency of *terra firme* forest corresponds to 25% of the total. Both forests decrease in frequency until 1,100 cal yr BP. From 62 cm (1,100 to 950 cal yr BP) muddy sediments were deposited (silty clay), which also suggest the predominance of sedimentation by decantation, which would be related to the maintaining and/or increasing the water level in Lake Cabaliana during the peak of seasonal flooding. The *varzea* forest shows an increase, rising to 40%, and *terra firme* forest recedes to 15%. At the end of this zone, these forests represent 30% and 25%, respectively. The *varzea* forest is characterized by an increase in *Alchornea* pollen (30%). Pollen of *Symmeria*, *Cecropia,* and Myrtaceae had been decreasing since the previous zone and *Symmeria* and *Cecropia* have been practically nonexistent since 1,100 cal yr BP. Myrtaceae becomes less represented at 1200 cal yr BP. *Pseudobombax, Sapium, Cassia*, *Tabebuia* and *Montrichardia* become more frequent (5% each) from 1200 cal yr BP to the end of this zone (Fig. 4). *Ryania, Luehea/Lueheopsis, Laetia* and *Hyeronima* have small isolated peaks of frequency in the interval of 1050 cal yr BP. The percentage of *Alternanthera* decreases from the previous zone then increases, reaching 10% at the upper limit with the preceding zone. The *terra firme* forest is represented by the frequency of Rutaceae, Sapotaceae, *Scleronema, Styrax, Pariana*, Asteraceae and Araceae (≤ 2% each) distributed predominantly in the interval of 1050-950 cal yr BP of this zone. In relation to the representative groups of *varzea* and *terra firme* forest, Moraceae/Urticaceae and Poaceae increase at 5% and 25%, respectively. There was an increase in pollen belonging to Cyperaceae and *Sagittaria*. Pteridophytes remained constant (5%), algae rose to 55% and fungi decreased significantly (40% to 10%). The total concentration was representative in this interval, but with a strong decrease in 900 cal yr BP (Fig. 4).

Zone IIIb (49-18 cm: 950-550 cal yr BP. Greyish silty clay)

The sedimentary process remains the same as in the previous subzone. The silty-clay lithology demonstrates that the basin of Lake Cabaliana still possesses episodes of elevation/maintenance of the water level (Fig. 2). In this subzone, the percentage of *varzea* forest varies between 35 - 50%, while the forest of *terra firme* experienced an increase, rising to 30% at 550 cal yr BP. Among the pollen of *varzea* forest, the frequency of *Symmeria* and *Cecropia* remain low until the subsequent zone. *Pseudobombax* increased, reaching 20% at the top of this subzone. Pollen of *Cassia* and *Gustavia* increased, but then decreased to less than 5% in 740 cal yr BP. *Sapium* began this subzone at low frequency and reached 5% by 600 cal yr BP. Among the elements of the *terra firme* forest, *Simaba, Doliocarpus, Desmodium* and Asteraceae are the most representative in this interval. Only Poaceae stands out in the *varzea* and *terra firme* forest group. Algae registered a peak of 50%, while fungi and spores remained constant. Thus, as in previous subzone, an intense increase in palynomorphs at this stage was expressed by the peak of total concentration in the interval of 800-700 cal yr BP, declining again to very low values (Fig. 4).

Zone IV (18-0 cm: 550 cal yr BP – until present. Silty clay)

The same lithology of the preceding zone remains in this interval with a high level of the water column in the basin of Lake Cabaliana (Fig. 2). There is a decrease in pollen of *varzea* vegetation to 25% while *terra firme* forest remains with 30% of the total until 450 cal yr BP. At the end of this zone, the *varzea* forest becomes established

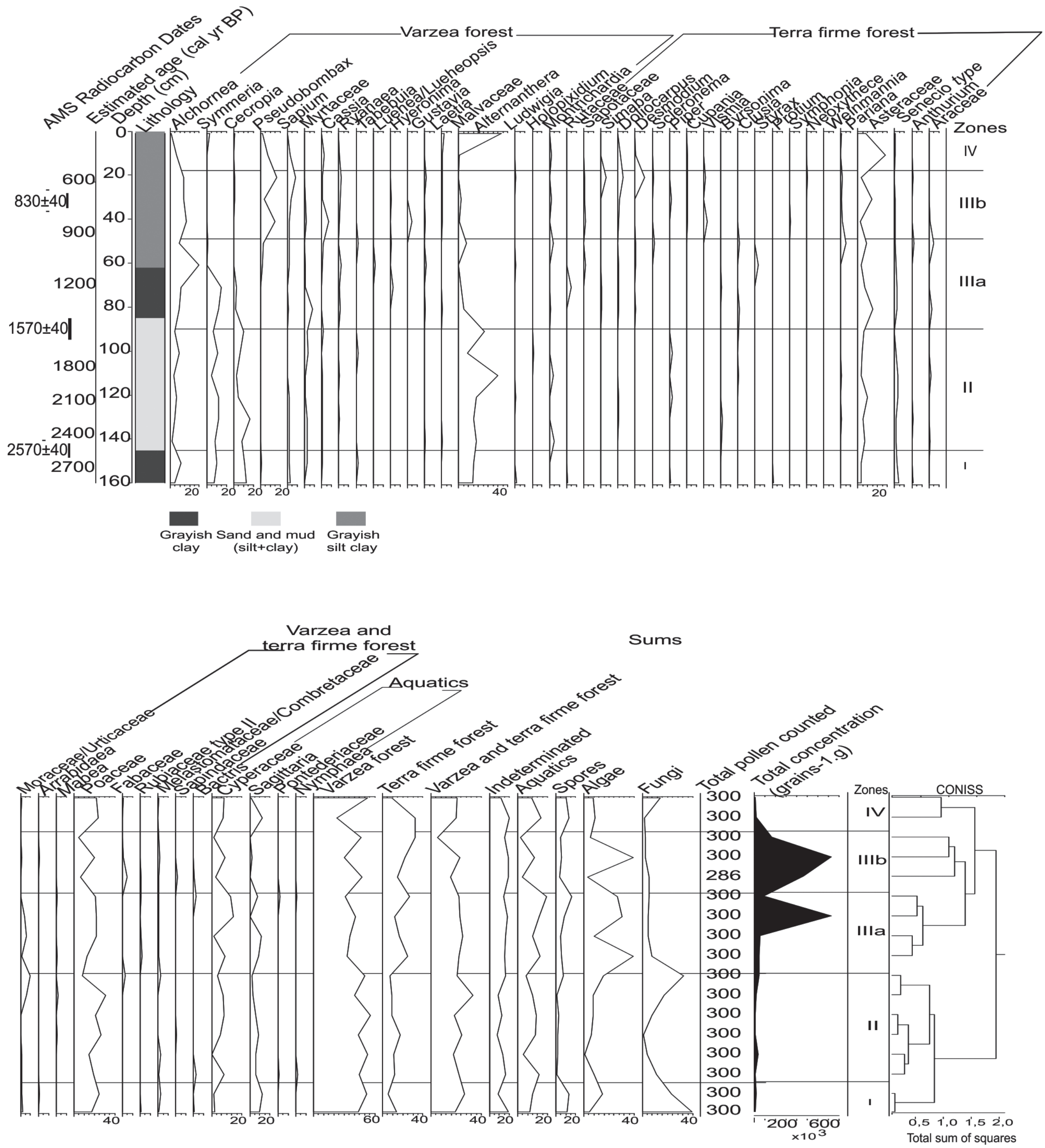

Figure 4. Palynological diagram with percentage rates and concentration rates of the highest frequencies (≥ 1%) in the PD-67 profile including timing, depth, lithology, and habit.

and represents 55% of total pollen, while the frequency of *terra firme* forest decays to 10%. This zone is characterised by decreases of *Alchornea, Pseudobombax and Sapium* pollen (<5% each), while *Alternanthera* returns and represents 45% of the sum. Pollen of *Simaba*, *Doliocarpus* and *Desmodium* (*terra firme* forest) had been decreasing since 550 cal yr BP. Asteraceae rises to 30%, but around 350 cal yr BP decays to 10%. Pollen of Poaceae represented 20% of the total terrestrial pollen. Cyperaceae maintained a frequency of 10% and *Sagittaria* reached a peak of 15% at 500 cal yr BP. Algae, pteridophytes and fungi present frequencies of 10% (Fig. 4). The decrease in palynomorphs reflects the lower values of total concentration, which is similar to the bottom of the profile.

Discussion

Source of pollen

The Solimões River has had little influence on the sedimentation of Lake Cabaliana, as indicated by the intermittent presence of Andean taxa *Weinmannia* and *Alnus,* whose frequency was less than 1% of the total sum (Fig. 3). Behling *et al*. (2001) also detected low percentages (0.6%) of Andean taxa *Weinmannia, Quercus and Myrica* in the sediments of Lago Calado (also on the left bank of the Solimões River) and Absy (1979) described the presence of *Alnus* in Costa da Terra Nova, located on the right bank of the Solimões River. It is unlikely that the presence of these taxa in the three analyzed profiles originated from air currents coming from the Andes in spite of them all having anemophilous dispersion. Andean pollen was found in low percentages (less than 1%) in suspension in the waters of the Solimões River near Manaus (2100 km from the Andes) and decreasing more and more with increasing distance from the source (Haberle 1997) .

The frequency of grass was generally high and extremely varied (Fig. 4), indicating that the banks of aquatic macrophytes are probably local, as proposed by Salgado-Labouriau (2007). In addition, Haberle (1997) showed that allochthonous pollen percentages of Poaceae in suspension in the Solimões River waters are very small at about 7%. The Cyperaceae followed the variations of grasses, which reinforces the idea of an autochthonous origin of grass pollen, as pointed out by Behling *et al*. (2001).

The distance between the lake and the main channel is another factor that can influence the charging of the filled sediments. Lakes drained directly by the main river course receive a higher rate of sediment during the flood period, while sedimentation is usually lower in lakes located further from the main channel systems (Irion *et al*. 1997), depending on the distance of the route.

Reconstruction of environmental changes

2,800–2,550 cal yr BP (Zone I)

In this zone, the sedimentation of fine material (clay) in the discharge area of the Piranha River delta is indicative of the predominance of deposition from decantation, which reflects low energy conditions (Fig. 2). According to the hydrological variations (flood and ebb) that are known to be present in the Central Amazon, this type of deposition occurred during a flood in the basin of Lake Cabaliana, which became a poorly drained lake.

Pollen of *Alchornea*, *Symmeria*, and *Cecropia* were predominant as were the herbaceous elements Poaceae, Asteraceae, and *Alternanthera*. The presence of *Arrabidaea,* Rubiaceae type II, Rutaceae, *Protium*, and *Symphonia* imply a *terra firme* forest and adjacent wetlands (Ayres 1993; Sá & Absy 2011) as suggested by the presence of pollen of *Bactris, Sagittaria*, and pteridophytes. The flood stage probably reached lower levels of about 3 to 4 m, in agreement with previous studies about the ecological succession of *varzea* forest proposed by Worbes *et al*. (1992); Worbes (1997) and Wittmann *et al*. (2004; 2006). The retreat of the water caused the exposure of submerged areas so that the herbaceous vegetation (grass, *Alternanthera*, Asteraceae) could establish. Once the herbaceous vegetation succession started, woody taxa and pioneers settled in monospecific groups of *Cecropia* (Parolin *et al*. 2002) and *Alchornea*. Moreover, the surroundings of Lake Cabaliana exhibited a rich mosaic of vegetation that resulted from the decrease in water level and geomorphological dynamics. The *terra firme* forest advanced toward the abandoned areas of *varzea* vegetation, thus increasing flower richness (Fig. 5) in this phase, as proposed previously (Kalliola *et al*. 1991; Wittmann *et al*. 2002; 2004; 2006).

2,550–1,450 cal yr BP (Zone II)

In this zone, the interpolated layers of sand (fine to medium) and clay are indicative of alternating periods of higher energy (during flooding period) and periods of lower energy (during the height of maximum flood), respectively (Fig. 2). These changes are likely associated with the hydrological cycle of the Solimões River. The sandy layers are reflexes of the major flow channel and, consequently, reflect greater transport and deposition of sand particles, while the intercalation of mud reflects a phase of low flow in the main channel during maximum flooding.

Since 2,550 cal yr BP, the *varzea* forest was predominant. The *varzea* forest was characterised by the pioneer elements *Cassia*, *Laetia*, and *Mabea* in addition to *Symmeria* and *Cecropia*. *Terra firme* vegetation was not well represented. The pollen data suggest an increase in water flow and entry of sand into the lake, possibly related to the increased volume of water in the Solimões River and in the secondary channels that form the delta. The rhythm of sediment deposition was remarkable (Fig. 2) because it points to rapid fluctuations in periods of flood and ebb where the peak of the flood is marked by the predominance of clay deposition. This process may limit the establishment of vegetation, thus leaving only plants adapted to these variations (i.e., short cycle crops such as grasses; Junk & Piedade 1997) and plants resistant to high sedimentation rates such as *Alchornea* (Kalliola *et al*. 1991). At 2,300 cal yr BP, sand sedimentation marked a relatively dry phase (Fig. 2) that was less intense than during 2,800-2,550 cal yr BP (Zone I). The Solimões River continued to show greater speed in flow and volume of water (lotic environment) that caused leakage to secondary channels that prevented the establishment of vegetation along the lakeshore. This phenomenon, therefore, caused the decrease in flower species richness (Fig. 5) during this phase. The water column possibly retracted 1 to 2 m, which is consistent with previous observations of the successional dynamics of *varzea* forest (Worbes *et al*. 1992; Worbes 1997; Wittmann *et al*. 2004; 2006). The slightly dry phase continued between 2,250-1,850 cal yr BP. The richness remained low despite the lower height of the water column (Fig. 5). Herbaceous vegetation, characterised by the expansion of floating macrophytes (Poaceae, Cyperaceae), *Sagittaria*, *Montrichardia and* Asteraceae and after growth of the pioneer plants *Alchornea* and *Cecropia*, predominated. The floating macrophytes settled on exposed areas, especially sand banks formed by the more intense discharge of the Solimões River. The rapid proliferation of herbaceous taxa may have led to the stabilization of the sediment, with *Cecropia* and *Alchornea* colonizing these areas later. *Alchornea* can produce adventitious roots (Barbosa *et al*. 2008), which would help in stabilizing vegetation and sediment. Simultaneously, the percentage of algae could have increased due to the decrease in the photic zone as a result of a lower water mirror (Putz & Junk 1997). At the end of the wetter range (1,850–1,450 cal yr BP), secondary succession continued, as indicated by the higher frequency of *Cecropia* and *Cassia,* and a drop in grasses. Moraceae/Urticaceae and Myrtaceae also increased, probably colonising clearings - topographically higher areas (high *varzea* forest) from which submerged vegetation left in the previous phase.

1,450-950 cal yr BP (Zone IIIa)

At this stage, the slight change in particle size from clay to mud (silt-clay) about 1,100 cal yr BP (Fig. 2) shows a slight increase in energy of Lake Cabaliana and defines the flooding period of the lake level followed by an initial period of ebb. From 1,400 to 1,100 cal yr BP, there was a decrease of the energy flow of the Solimões River and secondary channels due to the height of the flood and the predominance of fine clay deposition that is characteristic of lentic environments (lacustrine sedimentation). It is possible

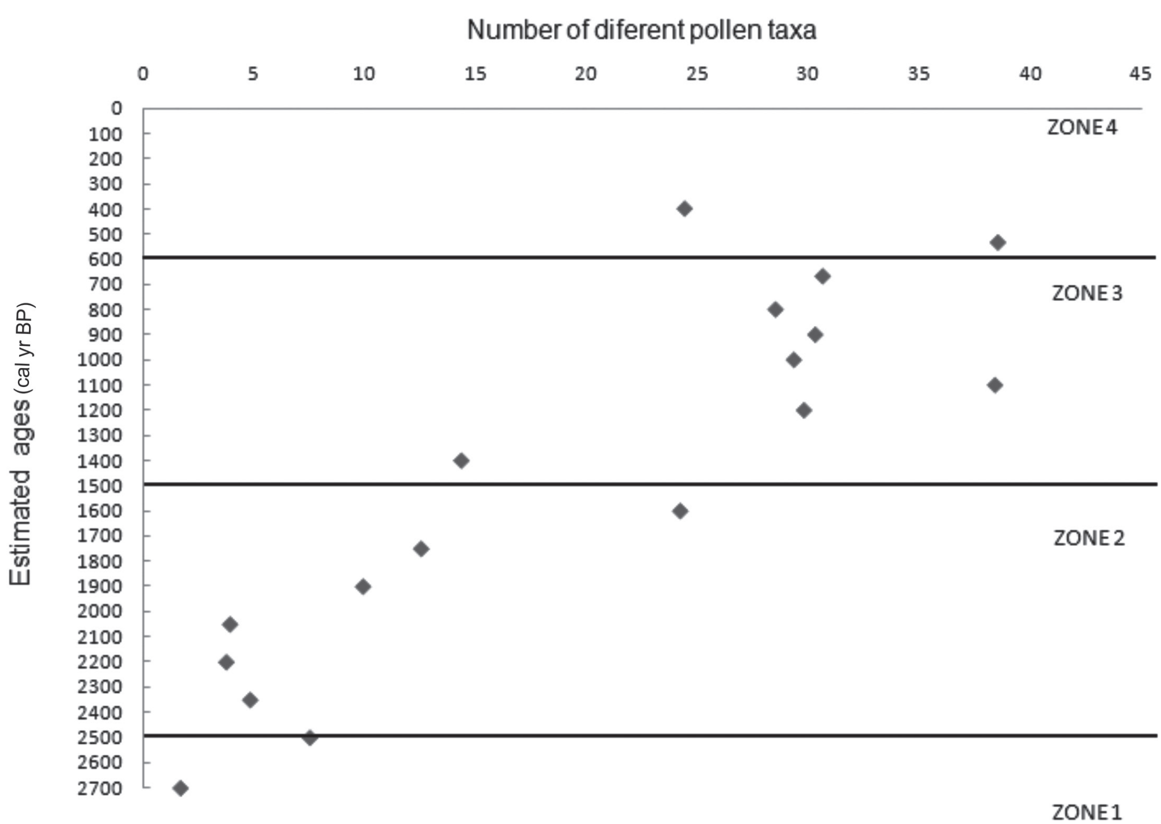

Figure 5. Richness of the terrestrial pollen taxa in the PD-67 samples.

that local precipitation was again the dominant influence on the sedimentation of Lake Cabaliana. Floristic richness increased slightly (Fig. 5), thus marking the advance of the succession of *varzea* forest (65% of terrestrial pollen sum). Continuity of vegetation succession of the *varzea* forest may have induced sediment deposition of fine particles caused by the decrease in water flow speed. The sequential process of grounding changed the topography of the areas surrounding the lake and the delta itself. The frequency of *Cecropia* decreased dramatically after 1,100 cal yr BP, and the frequency of *Pseudobombax* increased. Simultaneously, the highest percentages of *Laetia, Luehea/Lueheopsis* and *Ryanaea* were observed, indicating the advance of vegetative succession of *varzea* forest. The establishment of the following vegetational sere composed of late succession species of *varzea,* to the detriment of the initial species of *varzea* (Worbes *et al*. 1992), may indicate a decrease of 2 to 3 m in the water level, which is still maintained in the plain. A smaller representation of *Symmeria* and Myrtaceae since 1,200 – 500 cal yr BP would be related to its location near the front of the delta because the dynamics of the sediments caused the burial of roots and subsequent death of non-tolerant individuals (Junk & Piedade 1997; Parolin *et al*. 2004). The roots of the local vegetation act as a barrier to sediment flow, thus selecting species and opening paths for colonisation by nearby pioneer species such as *Alchornea* that are resistant to burial (Junk & Piedade 1997). The following elements of *terra firme* vegetation were present: Rutaceae, Sapotaceae, *Styrax, Scleronema*, *Anthurium, Araceae*, pteridophytes and *Pariana* (36%). *Pariana* is a typical bamboo of undergrowth of *terra firme* forest (Oliveira & Amaral 2005).

This floristic composition shows that the *terra firme* forest was directed toward the plain of Lake Cabaliana since 1,100 cal yr BP and colonised areas adjacent to high *varzea* forests. The observed conservation of lower levels of flooding allowed the increase in flower species richness (Fig. 5). A minor influence by flooding and geomorphologic dynamics resulted in increased diversity in the *varzea* forest. Therefore, this phase indicated a dry period similar to the range of 2,800–2,550 cal yr BP (Zone I) and therefore suggests that the flooding phase did not exceed 3 m.

950-550 cal yr BP (Zone IIIb)

In this phase the process of sedimentation is the same as the top of the previous zone (Fig. 2). The silty-clay lithology demonstrates that the basin of Lake Cabaliana exhibits events of elevation/maintenance of the water level. The ecological succession of *varzea* forest continued, and the following sere consisted of *Pseudobombax, Sapium, Gustavia* and *Laetia*. The climax *varzea* vegetation and late secondary taxa represented by *Pseudobombax*, *Laetia*, *Cassia* and *Vismia* began to become prevalent. *Terra firme* forest taxa including *Doliocarpus, Simaba*, *Scleronema, Cupania, Neoxythece* and *Desmodium* suggest the proximity or the mixture of elements of *terra firme* and *varzea* forest. The evidence suggests the shortest and lowest level of flooding compared to the previous stages.

550 cal yr BP until today (Zone IV)

At this stage, the predominance of silt-clay sediments (Fig. 2) in the area of delta discharge indicates a slight increase in river flow due to a decrease in water level probably after the flood peak from 1,500 to 1,200 yr BP. The floristic richness was lower (Fig. 5). The *terra firme* vegetation declined along with the high *varzea* forest. There was a predominance of pioneer *varzea* taxa including *Alchornea*, *Cassia*, and *Cecropia,* and the early secondary plant *Pseudobombax*. The grasses and sedges, *Alternanthera* and Asteraceae, were dominant. This plant community indicates that the elevation of the water level in the lake was about 3 m, thus inundating high floodplain areas and uplands. Flooding killed vegetation that was not adapted for anoxia, and it selected seeds and seedlings of flood-tolerant species (Wittmann & Junk 2003).

Late Holocene in Amazonia

The sedimentary and vegetational dynamics of Lake Cabaliana show that there might have been two drier periods represented by the effective decrease of precipitation at about 2,800 cal yr BP (Sá & Absy 2011) and 1,100 – 600 cal yr BP. The other stages, 2,300 cal yr BP and 1,400 – 1,100 cal yr BP, are indicative of less pronounced dry periods (i.e., minor variations in the water levels of Lake Cabaliana).

Lower rainfall conditions were also documented by Behling & Costa (2000) for the Curuá River in eastern Amazonia 2,500 yr BP where a *terra firme* forest developed. Sedimentological analysis indicated fine detrital mud, characteristic of lentic environments. The vegetation became similar to the current vegetation (*varzea* forest/igapo forest) with increasing water level, which was attributed to the rise in sea level. In the Tapajos River, since the last 4,300 yr BP, there has been no significant change in local vegetation related to climatic oscillations, although there were, possibly, changes in vegetation associated with human settlement in this region. Other proxies, geochemistry, Total Organic Carbon (TOC) and sedimentology, did not show shifts for this period (Irion *et al*. 2006). In the eastern Amazon, sedimentology (mud) has not indicated significant differences; the relevant proxy was the successional dynamics of vegetation. One of possible reasons for this lack of significant differences is the marine influence on the climatic dynamics of this eastern region.

As in the Tapajos River, no records of a dry phase were found for Lake Calado in the Central Amazon. According to Behling *et al*. (2001), sedimentological and vegetational control might be related to the rising waters of the Atlantic Ocean, causing a blockage of the Amazon River and the consequent rise of water level on the plain. Other factors that could be considered are the proximity to the Solimões River - Lake Calado has experienced an increase in input from the waters of the Solimões River; local rainfall and geomorphology of the area. Absy (1982) reported the ranges of 2,700-2,000, 700, and 400 yr BP as dry phases in the Central Amazon that were associated with decreases in effective precipitation. At Costa da Terra Nova on the left bank of the Solimões River, these dry phases were related to a reduction of water volume during the flood stage, however, the forces causing this event were not explained.

Palynological work in the Caqueta River, Colombia (Western Amazonia) suggest that the drainage system has changed in the Late Holocene. Changes in floristic composition indicate a reduction in river discharge that was a result of less precipitation between 4,000 and 3,000 yr BP and possibly between 2,700 and 1,900 yr BP (Behling *et al*. 1999; Hammen & Cleef 1992). In Piusbi Laguna (Western Amazon), the pollen record does not indicate changes in vegetation structure since 4,400 yr BP, thus ensuring more humid conditions for the entire Late Holocene.

The stage 2,550-1,450 yr BP at Lake Cabaliana corresponds to wetter conditions during which the discharge of the Solimões River was higher. The increase in granulometry for sand and mud associated with the drop of the species richness point to the increase in the discharge of the Solimões River and therefore the expansion of the wetlands. The expansion of the palm *Mauritia* was documented in the *Llanos Orientales* (Colombia) at about 2,300 yr BP and it may be related to an increase in rainfall or even the impact of human populations (Behling & Hooghiemstra 1998; Berrío *et al*. 2002).

Conclusions

In the Late Holocene the drainage system of the Solimões River was affected. Some of the effects included fluctuations in the flood pulse, in the flow channel (main and secondary) and on the sedimentation pattern, consequently causing variation in the structure and composition of the vegetation surrounding Lake Cabaliana. The distribution of both *varzea* and *terra firme* vegetation, and variation in sediment grain size (sand, silt and clay) from the PD-67 core sample, suggest two dry intervals occurred, one from 2,800 to 2,550 cal yr BP and another from 1,450 to 550 cal yr BP. Flooding during these dry periods was 3 to 4 m. During the wet phase from 2,550 to 1,400 cal yr BP, the flood pulse probably returned to its previous status and the flooding reached 5 to 6 m in height and submerged previously well-drained areas. The successional dynamics that occurred in Lake Cabaliana indicate that the actual *varzea* forest was established recently (last 550 cal yr BP), and is composed of a mosaic of different successional stages that are controlled by the intensity of the flood pulse in response to variations in local and regional precipitation.

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