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Vegetation and climate changes in the forest of Campinas, São Paulo State, Brazil, during the last 25,000 cal yr BP

Adriana Mercedes Camejo Aviles[1]*, Fresia Ricardi-Branco[2], Marie-Pierre Ledru[3], Luís Carlos Bernacci[4]

Abstract

A paleoenvironmental reconstruction was performed in a Riparian Forest near Campinas to improve knowledge of paleoclimate and paleoenvironment in the State of São Paulo, Brazil. A sediment core of 182 cm depth was collected in a swamp located within a Cerrado/Seasonal Semi-deciduous ecotone forest. The chronological frame is given by eight radiocarbon dating methods. Pollen and stable isotope analyses ($\delta^{13}C$ and $\delta^{15}N$) were performed all along the core. Modern pollen rain is based on five surface samples collected along the Riparian Forest. Results show a sequence of changes in vegetation and climate between 25 and 13 cal kyr before present (BP), and from 4 cal kyr BP to the present time, with a hiatus between 11 and 4 kyr cal BP. Drier climatic conditions characterized the late Pleistocene and early Holocene, although they had moisture peaks able to maintain an open forest. The Riparian Forest became fully installed from 4 cal kyr BP onward. Our results are in agreement with other regional studies and contribute to build a regional frame for past climatic conditions at the latitude of São Paulo.

KEYWORDS: Quaternary; palynology; riparian forest; late glacial; Holocene.

INTRODUCTION

Palynology applications in paleoenvironmental reconstruction studies have allowed us to understand the main processes involved in the distribution of species during global climatic fluctuations in the Quaternary (Bennett 1997). Studies underwent a significant change from monoproxy to multiproxy in the last decades, in which pollen grains incorporate anthropological, sedimentological and isotopic data, allowing more realistic inferences, as well as environment and climate reconstructions (Flantua *et al.* 2015).

In Brazil, the Quaternary researches with emphasis on paleoenvironmental reconstructions in climate change are significantly important, considering the country has the world's largest number of tropical species (IBGE 2004), consisted of diverse ecosystems that respond to climate changes. The forest studied here is part of this environment.

The oldest paleoclimatic record for Southeastern Brazil was identified at Colônia Crater (Ledru *et al.* 2015), in state of São Paulo. New studies are starting to be developed, and preliminary results indicate that sediments collected 14 meters deep present age approximately to 180 cal kyr before present (BP), which is an important record for Brazil and South America Quaternary (Ledru *et al.* 2015).

Cruz Jr. *et al.* (2006) studied relevant paleoclimatic records for Southeastern Brazil using isotopic data in speleothems (Santana/SP and Bouteverá/SC caves). Results show climatic variations of the last 110 cal kyr BP.

According to the paleoenvironmental records of Serra da Mantiqueira and Núcleo Curucutu in Serra do Mar (Pessenda *et al.* 2009), the climate conditions were cold and humid in Southeastern Brazil near the end of the Last Glacial Maximum (LGM). The records apply for Jacareí in Paraiba do Sul River Valley (Garcia 1994, Garcia *et al.* 2004) and São Paulo plateau (Bissa and Toledo 2015). From the Pleistocene end to the Holocene beginning, all of studies developed in the Paulista plateau (De Oliveira *et al.* 2014) showed evidence of temperature increase from 18,000 cal yr BP, with the stabilization of climatic conditions in the last 8,000 cal yr BP.

During the Holocene, the pollen record of Jacareí/SP showed cool and humid climatic conditions between 9,700 and 8,240 cal yr BP, followed by warmer episodes between 8,240 and 3,500 cal yr BP, and then back to cooler conditions between 3,500 and 1,950 cal yr BP (Garcia *et al.* 2004). The pollen analyses of a fluvial terrace of Mogi Guaçu River located

[1]Programa de Pós-graduação em Geociências, Instituto de Geociências, Universidade Estadual de Campinas – Campinas (SP), Brazil. E-mail: adrianacamejo@ige.unicamp.br

[2]Departamento de Geologia e Recursos Naturais, Instituto de Geociências, Universidade Estadual de Campinas – Campinas (SP), Brazil. E-mail: fresia@ige.unicamp

[3]Institut des Sciences de l'Entreprise et du Management, Université de Montpellier, Centre national de la recherche scientifique, Instituto Francês de Pesquisa para o Desenvolvimento (IRD), École Pratique des Hautes Études – Montpellier, France. E-mail: marie-pierre.ledru@ird.fr

[4]Centro de Pesquisa e Desenvolvimento de Recursos Genéticos Vegetais, Instituto Agronômico de Campinas – Campinas (SP), Brazil. E-mail: bernacci@iac.sp.gov.br

*Corresponding author.

in Jataí Ecological Station (JEE) of the Forestry Institute, State of São Paulo, show drier conditions at the beginning of Holocene characterized by open-field vegetation with fire incidence (Souza *et al.* 2013), followed by an expansion of the Riparian Forest of 2,183 cal yr. BP, as well as installation of humid climate similar to the current one (Souza *et al.* 2013).

Most palynological studies in Southeastern Brazil were concentrated in mountainous and coastal zones, specifically State of São Paulo, with the exception of JEE (Souza *et al.* 2013). Our research aims to provide new paleo-ecological data inland São Paulo related to Riparian Forest located within the Cerrado/Seasonal Semi-deciduous ecotone forest. Thus, the river course is a place of great importance, due to the main migrations of vegetal species that happen in periods of climate change at the Riparian Forests (Oliveira-Filho *et al.* 2015). The studied site is located on the margins of Quilombo Stream, Santa Elisa Farm, Campinas. The study allowed characterizing vegetation and climate evolution in the last 25 cal kyr BP.

STUDY AREA

Location

The analyzed core was collected inside the Riparian Forest according to Carvalho *et al.* (2013) and located at Santa Elisa Farm in São Paulo State (22°51’22.08”S, 47°05’35.50”W, 15 m a.s.l.). The forest covers an area of 6 ha along the Quilombo Stream (Fig. 1) and belongs to the Agronomic Institute of Campinas (IAC, acronym in Portuguese), in the city of Campinas (São Paulo).

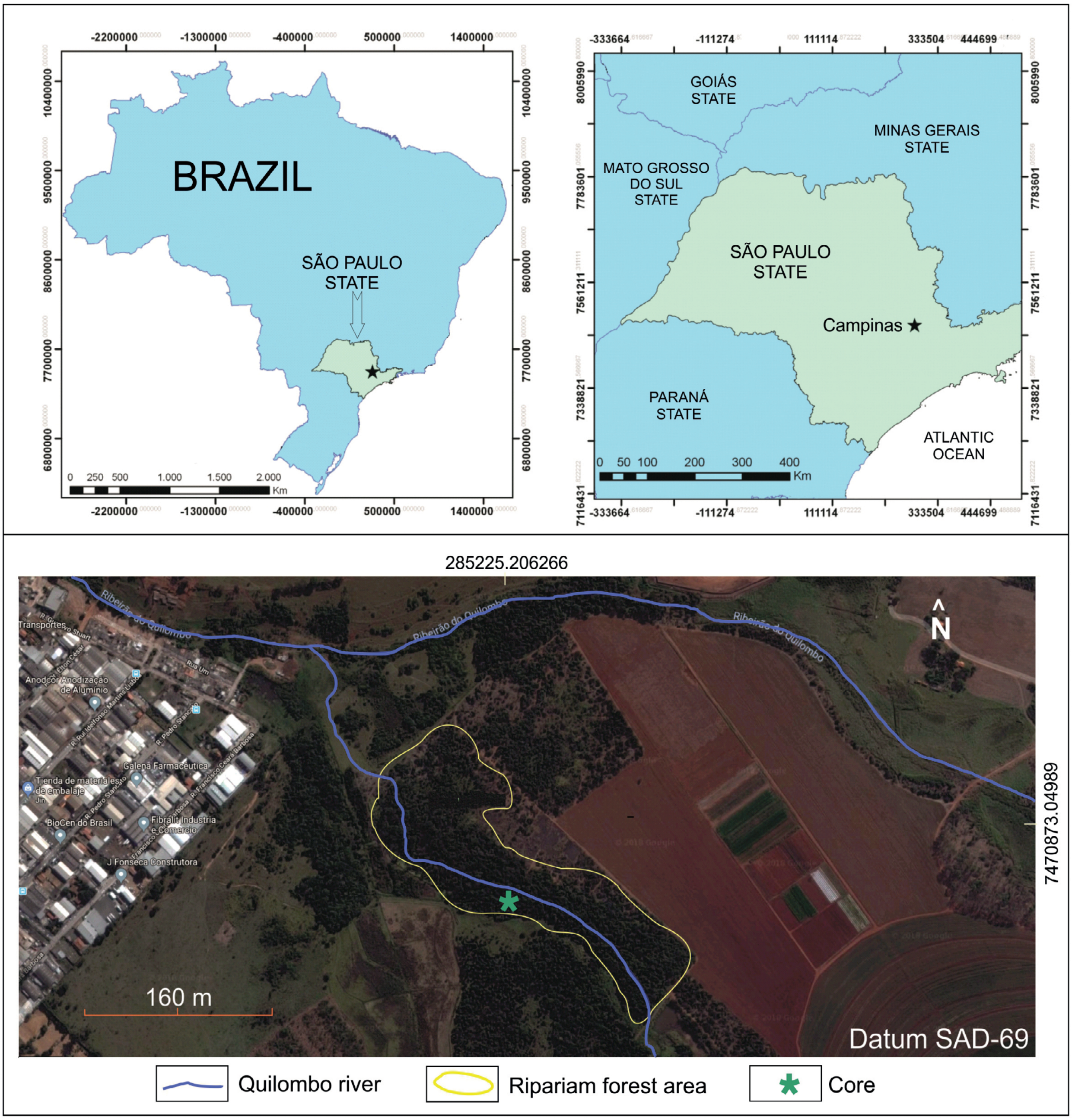

Figure 1. Map of the study area showing the core location at Santa Elisa Farm Study Site, Campinas, state of São Paulo.

Climate

The tropical rainfall system experiences a pronounced seasonal cycle in the region of Campinas (Garreaud *et al.* 2009). It presents a rainy season during the austral summer (from March to October) related to the South American Summer Monsoon activity over Southeastern Brazil, and a dry season during the austral winter (September to April). The mean of annual precipitation is 1,400 mm and of annual temperature varies between 23.1°C in January and 17.1°C in July.

Current vegetation

Currently, vegetation in the area of Campinas shows high degree of human impact. Thus, fragments of native vegetation represent only 2.6% of the territory, which is almost entirely cultivated (Kronka *et al.* 2005). Vegetation at Santa Elisa Farm is a transition zone between Cerrado (Savanna) and Seasonal Semi-deciduous Forest (Penha 1998, Felfili *et al.* 2001, Rodrigues *et al.* 2004, Ferreira *et al.* 2007, Siqueira and Durigan 2007, Mendonça *et al.* 2008, Carvalho *et al.* 2013).

The environmental conditions that determine the distribution of Cerrado, Seasonal Semi-deciduous Sorest, and Riparian Forest are dry season length, winter temperatures, and soil drainage. Botanical surveys within the Riparian Forest described 35 families of angiosperms among 80 species, and the dominant families are: *Fabaceae*, *Myrtaceae*, *Meliaceae*, *Lauraceae*, and *Rutaceae*. They represent 41% of total species (Oliveira-Filho *et al.* 1990, Ferreira *et al.* 2007, Carvalho *et al.* 2013, Penha 1998, Rodrigues *et al.* 2004).

MATERIALS AND METHODS

Chronology

The chronology is based on eight radiocarbon ages (Tab. 1), three sediment samples were analyzed in the laboratory of ^{14}C-AMS Beta Analytic (Miami, USA), and five samples of Humina extracted from the Laboratory of Paleo-Hydrogeology of the Institute of Geosciences from Universidade Estadual de Campinas — Unicamp (Campinas, Brazil) were analyzed in the laboratory of ^{14}C AMS — University of Georgia (Athens, USA). ^{14}C ages were calibrated using the CLAM 2.2 software (Blaauw 2010, version 2.2) with the SHCal13 calibration curve for the atmospheric southern hemisphere (Hogg *et al.* 2013). The result was based on a 95% probability of 2 sigma (Fig. 2).

Stable nitrogen and carbon isotopes

Measures of δ^{13}C and δ^{15}N isotopic composition were performed at the Stable Isotope Laboratory of the Center for Nuclear Energy in Agriculture — CENA-USP (Piracicaba, Brazil). We used 1 g of sample for 27 levels (Tab. 2), which was distributed throughout the core (Fig. 3), as follows: in the upper 90 cm, the sampling interval is 10 cm; between 90 and 1.78 cm, it is 5 cm. Results of the isotopic ratio were expressed in δ unit (‰) and based on the Vienna-Pee-Dee-Belemnite (PDB) international standard, referring to two determinations with an accuracy of ±0,2‰ (Vidotto *et al.* 2007).

Palynological analyses

For the palynological analysis of Santa Elisa core, we used intervals of 2 cm for the first 90 cm and 5 g of sediment. The samples were chemically processed following Faegri and Iversen (1989), where they were oven dried for 4 hours

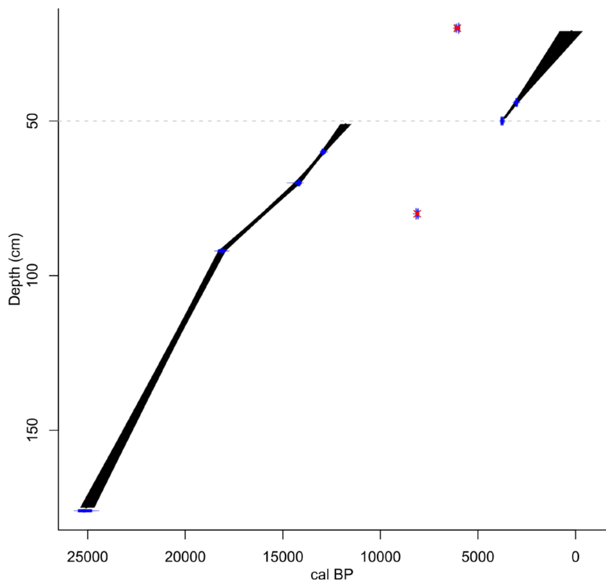

Figure 2. Age-depth model of linear interpolation based on ^{14}C BP ages with 95% confidence intervals ranging from 138 to 750 years (345 years on average). Ages at 80 and 20 cm were excluded; they are indicated with a red point considered as noise.

Table 1. Radiocarbon ages obtained from Santa Elisa Farm Core. ^{14}C dates were calibrated using CLAM 2.2 (Blaauw 2010) and SHCal13 calibration curve for the Southern hemisphere (Hogg et al. 2013).

Sample/Depth (cm)	Age 14C (years BP)	Age 14C Cal. 2 δ (years BP)	13C/12C	Laboratory code
20	5,263 ± 27	5,910–6,022	-18.19‰	UGAMS-28843
42–44	2,890 ± 30	2,863–3,066	-19.9‰	BETA-314745
50	3,479 ± 27	3,607–3,734	-19.25‰	UGAMS-28844
60	11,065 ± 31	12,755–13,007	-15.76‰	UGAMS-28845
70	12,277 ± 32	15,026–15,315	-16.63‰	UGAMS-28846
80	7,330 ± 23	15,026–15,315	-18.37‰	UGAMS-28847
90–92	14,910 ± 60	8,023–8,170	-19.8‰	BETA-314746
174–176	20,850 ± 100	24,657–25,424	-16.9‰	BETA-314747

at ~60ºC. HF was added for the dissolution of silicates (leaving for 24 hours). In addition, warm HCl was included for colloidal silica removal, then it was washed with 10% KOH for the destruction of humic acids and amorphous organic matter. The samples were dehydrated with glacial acetic acid, and finally acetolysis. An average of 10 drops of glycerin was added to the final residue.

Table 2. Results of stable isotopes analyses

Depth (cm)	TN (%)	^{15}N (‰)	C-total (%)	^{13}C (δ/pdb)
0	0.61	4.33	7	-24.42
10	0.36	6.13	4.28	-21.68
20	0.2	6.72	3.44	-18.19
30	0.16	7.53	2.64	-18.7
40	0.37	5.83	4.81	-22.1
50	0.24	5.55	4.03	19.25
60	0.17	5.55	4.28	-15.76
70	0.1	5.8	2.02	-16.63
80	0.1	5.58	1.67	-18.37
90	0.03	5.27	0.46	-19.69
100	0.02	7	0.36	-21.48
104	0.02	6.22	0.33	-21.53
110	0.02	8.14	0.32	-22.12
116	0.02	7.63	0.33	-22.11
120	0.02	9.36	0.32	-22.58
124	0.02	7.88	0.31	-22.64
130	0.07	4.59	1.32	-17.85
134	0.08	5.26	1.21	-18.3
140	0.02	9.21	0.31	-22.49
146	0.02	7.28	0.33	-22.26
150	0.02	7.49	0.32	-22.81
154	0.02	7.37	0.28	-21.77
160	0.02	5.49	0.25	-22.13
166	0.02	5.68	0.27	-21.03
170	0.01	7.21	0.23	-20.46
174	0.02	6.18	0.14	-17.44
178	0.02	6.15	0.31	-15.99

After preparing the material, non-permanent microscopy slides sealed with maximal limits of residues (LMR) of histopaque fast drying glue were prepared using a residual amount of 50 microliters to calculate the concentration following the mathematical method described by Cour (1974).

About 300 pollen grains were counted. Data were expressed as a percentage of each taxon in relation to the partial sum that includes the arboreal (PA), non-arboreal/herbaceous (NPA), and indeterminate pollen grains. The rate of aquatic plants and spore grains were excluded. Spores are generally removed from the sum, due to their large production and local significance. Percentages of spores and aquatic plants were calculated as to the total sum including AP, NPA, indeterminate pollens, aquatic plants and spores.

Modern pollen rain was collected following a type of random sampling at the study site, with the total of five surface sediment samples.

A reference collection with 24 pollen types (Tab. 3) was performed for Santa Elisa Farm site considering the botanical inventory proposed by Carvalho *et al.* (2013). Mature flowers were collected in the herbarium of Unicamp (UEC). It was made in permanent slides with Kisser Glycerinated Gelatin (Erdtman 1971) and sealed with preheated paraffin.

RESULTS

Core description

A core of 182 cm length named Santa Elisa was extracted using a manual probe on the swampy banks of Quilombo Stream. Changes in color, texture and presence of plant remains were observed in the sediment as follows (Fig. 3):

- 182 to 172 cm: dark gray color, composed of clay and presence of iron oxides dispersed in the matrix;
- 172 to 104 cm: light gray color and composed of clay;
- 104 to 90 cm: dark gray color, composed of clay and presence of iron oxides dispersed in the matrix;
- 90 to 0 cm: black color, composed of clay organic sediments that are not compacted, and abundant plant remains.

Chronology

The core basis shows age of 25,040 cal yr BP. Two chronological inversions were identified: one at 80 cm depth with

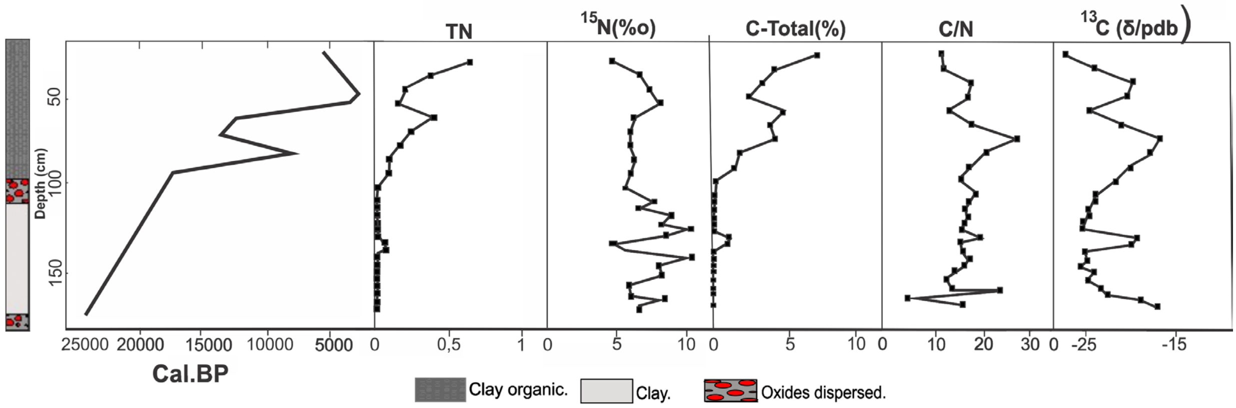

Figure 3. Lithology ages of 14C BP and variations relative to depth of TN (%), 15N (‰), Carbon [C-total (%) and 13C (δ/pdb)] and C/N.

Table 3. List of plant species of Santa Elisa Farm from Carvalho et al. (2013) incorporated in the pollen Reference Collection at the Institute of Geosciences, Universidade Estadual de Campinas (Unicamp).

Family	Species	Growth Habit	UEC Voucher
Acanthaceae	*Ruellia brevifolia* (Pohl) C. Ezcurra	Shrub	77977
Amaranthaceae	*Chamissoa altissima* (Jacq.) Kunth	Vine	26759
	Amaranthus retroflexus L.	Herb	40322
Annonaceae	*Duguetia lanceolata* A.St.-Hil.	Shrub	60172
	Xylopia aromatica (Lam.) Mart.	Shrub	33281
Apocynaceae	*Forsteronia glabrescens* Müll.Arg.	Vine	128083
Araliaceae	*Dendropanax cuneatus* (DC.) Decne. & Planch.	Tree	136977
Arecaceae	*Syagrus romanzoffiana* (*Cham.*) *Glassman*	Tree	128732
Asteraceae	*Ageratum conyzoides* L.	Herb	181832
	Erechtites valerianifolius Link ex Spreng.	Herb	120111
Bignoniaceae	*Anemopaegma chamberlaynii* (Sims) Burean. & K. Schum.	Vine	168626
	Handroanthus cf. *heptaphyllus*	Tree	829
	Jacaranda micrantha Cham.	Tree	136219
	Lundia obliqua Sond.	Vine	108782
	Mansoa difficilis (Cham.) Bureau & K.Schum.	Vine	151150
	Pyrostegia venusta (Ker Gawl.) Miers	Vine	132023
Boraginaceae	*Cordia ecalyculata* Vell	Tree	997
Burseraceae	*Protium heptaphyllum* (Aubl.) Marchand.	Tree	059437
Cactaceae	*Pereskia aculeata* Mill.	Vine	38379
Celastraceae	*Maytenus aquifolium* Mart.	Shrub	506771
Chlorantaceae	*Hedyosmum brasiliense* Mart. ex Miq.	Shrub	159981
Clusiaceae	*Calophylum brasiliensis* Cambess.	Tree	125495
Cucurbitaceae	*Wilbrandia verticillata* (Vell.) Cogn.	Vine	3971
Euphorbiaceae	*Actinostemon klotzschii* (Didr.) Pax.	Shrub	110913
	Croton floribundus Spreng.	Tree	105729
	Croton priscus Spreng.	Tree	173231
	Dalechampia pentaphylla Lam.	Vine	90366
	Dalechampia triphylla Lam.	Vine	168520
	Pachystroma longifolium (Nees) I.M.Johnst.	Tree	4945
	Sapium glandulosum (L.) Morong	Tree	124428
	Sebastiania brasiliensis Spreng.	Shrub	37556
	Tragia sellowiana (Baill.) Müll. Arg.	Vine	40668
Leguminosae	*Anadenanthera colubrina* (Vell.) Brenan	Tree	141859
	Chamaecrista flexuosa (L.) Greenes.	Shrub	119769
	Crotalaria paulina Schrank.	Shrub	123546
Malpighiaceae	*Banisteriopsis stellaris* (Griseb.) B.Gates	Vine	163362
	Byrsonima sp.	Tree	29474
Malvaceae	*Abutilon fluviatile* (Vell.) K.Schum.	Shrub	64231
Melastomataceae	*Ceiba speciose* (A. St.-Hil.) Ravenna	Tree	061815
	Miconia chamissois Naudin	Shrub	10718
Meliaceae	*Cedrela fissilis* Vell.	Tree	28836
	Trichilia catigua A. Juss.	Shrub	060488
	Trichilia claussenii C.DC.	Shrub	108412
	Trichilia elegans A. Juss.	Shrub	49464
Moraceae	*Maclura tinctoria* (L.) Don ex Steud.	Shrub	62326
	Sorocea bonplandii (Baill.) W.C. Burger, Lanjow & Wess. Boer.	Tree	53173
	Compomanesia guazumifolia (Cambess.) O.Berg.	Tree	151413
Myrtaceae	*Calyptranthes concinna* DC.	Shrub	108434
	Myrciaria floribunda (H.West ex Willd.) O.Berg.	Shrub	182667
Sapotaceae	*Chrysophyllum gonocarpum* (Mart. & Eichler) Engl.	Tree	2071
Urticaceae	*Boehmeria caudata* Sw.	Shrub	67612
Vochysiaceae	*Vochysia tucanorum Mart.*	Tree	24807

age of 8,096 cal yr BP, possibly derived from bioturbation, and other at 20 cm depth, with age of 5,966 cal yr BP, which may be attributed to carbon enrichment of older ages. We observed a hiatus between 12,881 cal yr BP and 3,670 cal yr BP (Tab. 1, Fig. 2).

Total organic carbon, total nitrogen

Total organic carbon (TOC) concentration shows progressive enrichment along the core, due to interaction between organic matter replacement and decomposition (Pessenda *et al.* 1996). The minimum value of TOC (0.14%) in the 174 cm depth, and the maximum value of TOC (7%) was observed in the 0–2 cm depth, with an average of 1.53% (Tab. 3, Fig. 3). The concentration of total nitrogen (TN) percentage (Tab. 3, Fig. 3) shows a minimum value of 0.02% at various depths of the core, ranging from 178 (25 cal kyr BP) to 140 cm (22 cal kyr BP), and from 124 (20 cal kyr BP) to 100 cm (18 cal kyr BP) with a maximum value of 0.63% in the 0–2 cm interval and an average of 0.10%. The vegetal tissue deposition justifies the high N values on the core surface (Pessenda *et al.* 1996). Variations in nitrogen concentration follow those of carbon, as it is seen in the 30-60 cm (1,308–12,924 cal yr BP) and 125-40 cm (20,889–2534 cal yr BP) intervals with an increase of TOC % and TN % content. The relationship suggests significant organic matter deposition. Nevertheless, TOC and TN tend to decrease as depth increases.

$\delta^{13}C$ of sedimentary organic matter

The carbon isotope approach was used to observe changes in the distribution of C_3 and C_4 plant communities (Pessenda *et al.* 2009).

High enriched values of $\delta^{13}C$ are recorded for the core base, as -15.99‰, age of ^{14}C 20,850 +- 100 yr BP (24,781–25,503 cal yr BP), characteristic of open vegetation dominated by Poaceae, as seen in Figure 3, Table 2. A progressive impoverishment of $\delta^{13}C$ is observed from the core base to 140 cm (22,144 cal yr BP) depth associated with a mixture of C_3 and C_4 plants. At 140–125 cm depth (22–20 cal kyr BP), an enrichment of $\delta^{13}C$ was observed in the -18.3 to -17 interval. A depletion of $\delta^{13}C$ with values of -22.64 to -21.48‰ is observed between 125 and 100 cm (20–18 cal kyr BP). Between 100 and 60 cm (18–12 cal kyr BP), the $\delta^{13}C$ ranges from -21.48‰ to -15.76‰ with average of -18.38‰. At this stage, there are four ^{14}C ages at 90 cm of 14,910 ± 60 ^{14}C yr BP (15,026–15,315 cal yr BP), 80 cm of 7,330 ± 23 ^{14}C yr BP (8,044–8,144 cal yr BP), 70 cm of 12,277 ± 32 ^{14}C yr BP (14,047–14,376 cal yr BP), and 60 cm of 11,065 ± 31 ^{14}C yr BP (12,809–3,043 cal yr BP). In the 60–40 cm (13–3 cal kyr BP) interval, the $\delta^{13}C$ values showed a trend of impoverishment with values ranging from -15.76 to -22.1‰.

In the 40-cm top (2,941–3,081 cal yr BP to the present time), the $\delta^{13}C$ range from -22.1 to -24.42‰. At this stage, we found ^{14}C age at 20 cm of 5,263 ± 27 ^{14}C yr BP (5,937–6,031 cal yr BP) that is a chronological inversion associated with carbon enrichment of older ages.

Modern pollen rain

Twenty-five pollen types representing 20 families have been identified in the five surface sediment samples in the palynological diagram (Fig. 4).

- Point 1 (Riparian Forest, 22°51'21.15"S/47°5'37.11"W, 421 grains in total, including AP, NAP, indeterminate, and spores). The arboreal pollen grains contributed with 53% of total sum, belonging to *Fabaceae* [*Crudia* sp. (11%), *Crotalaria* sp. (1%) and *Mimosa* sp. (11%)]; *Euphorbiaceae* [*Alchornea* sp. (5%), and *Euphorbia* sp. (1%)]; *Chloranthaceae* [*Hedyosmum* sp. (6%)]; *Melastomataceae/Combretaceae* (4%); *Myrtaceae* (3%); *Podocarpaceae* [*Podocarpus* sp. (3%)], and *Anacardiaceae* [*Lithraea sp.* (2%)]. Other families showed 1% as *Apocynaceae* (1%);

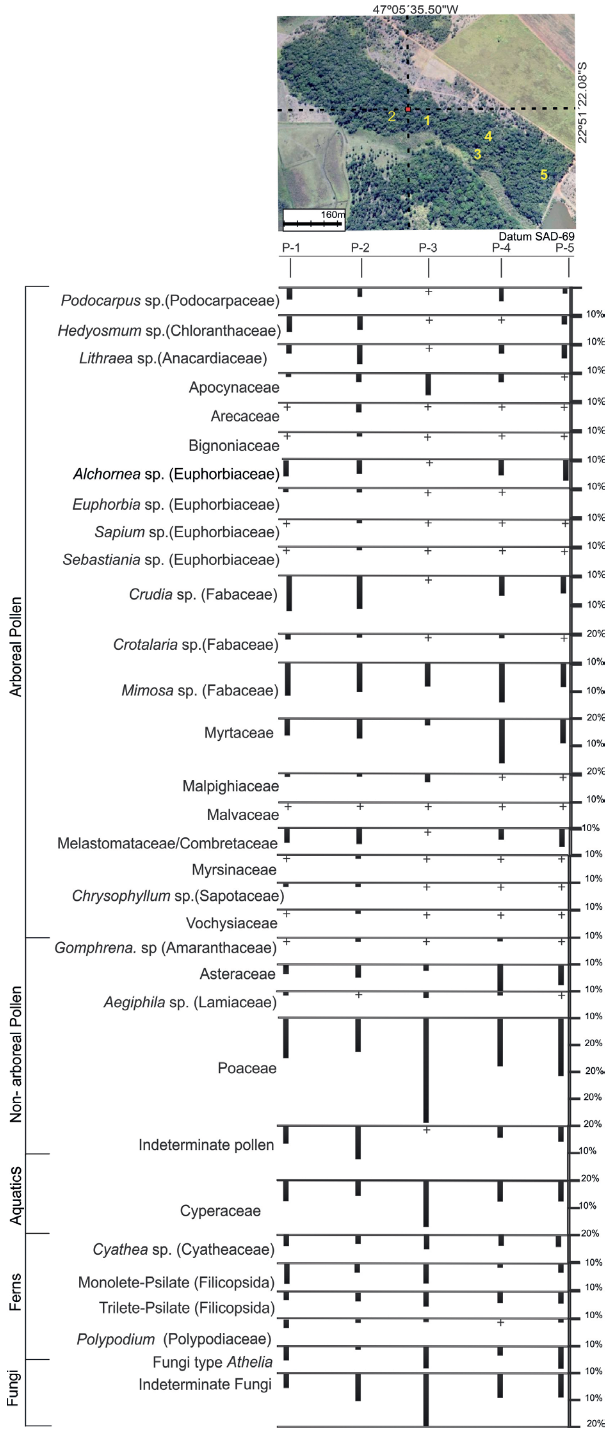

Figure 4. Diagram presenting the results of surface pollen samples collected along the riparian forest, Quilombo stream, watershed, near water course, in Campinas, São Paulo state, Brazil. (+) represents the taxa with less than 1% representation.

Malphigiaceae (1%) and *Sapotaceae* [*Chrysophyllum* sp. (1%)]. Families with less than 1% (+) were *Euphorbiaceae* [*Sapium* sp. (+), *Sebastiania* sp. (+)]; *Arecaceae* (+); *Bignoniaceae* (+); *Malvaceae* (+); *Myrsinaceae* (+), and *Vochysiaceae* (+). Non-arboreal pollen grains accounted for 41%, including *Poaceae* (31%); *Asteraceae* (9%); *Lamiaceae* [*Aegiphila* sp. (1%)], and *Amaranthaceae* [*Gomphrena* sp. (+)]. 6% were indeterminate pollen grains. Finally, among aquatic plants, *Cyperaceae* (12%), fern spores (15%), *Athelia* fungi spores (5%), and indeterminate fungi spores (9%);

- Point 2 (Riparian Forest, 22°51'25.82"S/47°5'29.66"W, 587 grains in total, including AP, NAP, indeterminate, and spores). The arboreal pollen grains contribute with 58% of total sum, belonging to *Fabaceae* [*Crudia* sp. (9%), *Crotalaria* sp. (1%), *Mimosa* sp. (10%)]; *Euphorbiaceae* [*Alchornea* sp. (4%), *Euphorbia* sp. (1%), *Sapium* sp. (1%), and *Sebastiania* sp. (1%)]; *Myrtaceae* (7%); *Anacardiaceae* [*Lithraea sp.* (7%)]; *Melastomataceae/Combretaceae* (5%); *Chloranthaceae* [*Hedyosmum* sp. (4%)]; *Arecaceae* (3%); *Podocarpaceae* [*Podocarpus sp.* (2%)], and *Apocynaceae* (2%). Other families showed 1% representation as *Malphigiaceae* (1%); *Myrsinaceae* (1%); *Vochysiaceae* (1%); *Sapotaceae* [*Chrysophyllum* sp. (1%)], and *Bignoniaceae* (1%). *Malvaceae* (+) was the family with less than 1%. The non-arboreal pollen grains accounted for 31%, with *Poaceae* (23%); *Asteraceae* (6%), and *Amaranthaceae* [Gomphrena sp. (2%)]. *Lamiaceae* [*Aegiphila* sp. (+)] was the family with lower than 1%. Indeterminate pollen grains accounted for 11%. Finally, among aquatic plants, *Cyperaceae* (8%), fern spores (8%), *Athelia* fungi spores (1%), and indeterminate fungi spores (10%);
- Point 3 (Riparian Forest, 22º51'25.74"S/47º5'28.68"W, 238 grains in total, including AP, NAP, indeterminate pollen, and spores). At this point, a few palynomorphs were found with an increase of non-arboreal pollen to 81%, dominated by *Poaceae* (72%); *Lamiaceae* [*Aegiphila* sp. (7%)], and *Asteraceae* (2%). The AP grains decreased to 19% of the total sum, dominated by *Fabaceae* [*Mimosa* sp. (8%)]; *Apocynaceae* (5%); *Melastomataceae/Combretaceae* (3%); *Malphigiaceae* (2%), and *Myrtaceae* (1%). Among aquatic plants, *Cyperaceae* family was dominant with 19%, fern spores, 17%; *Athelia* fungi spores, 11%; and indeterminate fungi spores, 18%;
- Point 4 (Riparian Forest, 22°51'27.21"S/47°5'27.76"W, 371 grains in total, including AP, NAP, indeterminate pollen, and spores). The arboreal pollen grains contribute with 50% of total sum, belonging to *Fabaceae* [*Crudia* sp. (7%), *Crotalaria* sp. (1%), and *Mimosa* sp. (10%)]; *Euphorbiaceae* [*Alchornea* sp. (7%)]; *Myrtaceae* (15%); *Melastomataceae/Combretaceae* (3%); *Podocarpaceae* [*Podocarpus* (4%)]; *Apocynaceae* (1%), and *Anacardiaceae* [*Lithraea sp.* (1%)]. Families with less than 1% (+) were *Euphorbiaceae* [*Euphorbia* sp. (+), *Sebastiania* sp. (+), and *Sapium* sp. (+)]; *Malpighiaceae* (+); *Malvaceae* (+); *Vochysiaceae* (+), and *Sapotaceae* [*Chrysophyllum* sp. (+)]. Non-arboreal pollen grains accounted for 46%, with *Poaceae* (29%), *Asteraceae* (10%), *Lamiaceae* [*Aegiphila* sp. (2%)], and *Amaranthaceae* [*Gomphrena* sp. (2%)], indeterminate pollen grains (5%). Among aquatic plants, *Cyperaceae* (12%), fern spores (8%), *Athelia* fungi spores (5%), and indeterminate fungi spores (12%);
- Point 5 (Riparian Forest, 22°51'27.21"S/47°5'27.76"W, 421 grains in total, including AP, NAP, indeterminate, and spores). AP grains contribute with 39% of total sum, belonging to *Fabaceae* [*Crudia* sp. (4%), and *Mimosa* sp. (7%)]; *Euphorbiaceae* [*Alchornea* sp. (7%), and *Euphorbia* sp. (1%)]; *Myrtaceae* (8%); *Anacardiaceae* [*Lithraea sp.* (4%)]; *Melastomataceae/Combretaceae* (3%); *Chloranthaceae* [*Hedyosmum* sp. (2%)]; *Podocarpaceae* [*Podocarpus sp.* (2%)]. Families with less than 1% (+) were *Myrsinaceae* (+); *Fabaceae* [*Crotalaria* sp. (+)]; *Euphorbiaceae* [*Sebastiania* sp. (+)]; *Apocynaceae* (+); *Arecaceae* (+); *Bignoniaceae* (+); *Malvaceae* (+); *Malphigiaceae* (+), and *Sapotaceae* [*Chrysophyllum* sp. (+)]. NAP grains accounted for 56%, with *Poaceae* (41%); *Asteraceae* (10%); *Lamiaceae* [*Aegiphila* sp. (2%)], and *Amaranthaceae* [*Gomphrena* sp. (2%)]; indeterminate pollen grains (5%). Among aquatic plants, *Cyperaceae* with 15%, fern spores (8%), *Athelia* fungi spores (5%), and indeterminate fungi spores (14%).

Fossil pollen

We observed four pollen zones based on changes in pollen frequency and $\delta^{13}C$ isotopic results, numbered from I (older) to IV (younger), as seen in Figure 5. Forty-three pollen types belonging to 32 families were identified in four pollen zones:

- Zone I: 15 samples, 90 and 60 cm depth, between -17,770 and 12,924 cal yr BP. It is characterized by the absence of palynomorphs in 13 samples and low concentration in the sample at the 78-76 cm depth interval. The total number of pollen grains is 86, which represents 230 pollen grains per grams of sediment. 55% of arboreal pollen, 30% of non-arboreal pollen, and 15% of indeterminate pollen. Spores accounted for 47 to 32%, and fungi from 21 to 26%. Arboreal pollen grains identified in the zone belong to *Malpighiaceae* [*Byrsonima* sp. (18 to 4%)]; *Myrtaceae* (13 to 8%); *Sapotaceae* [*Chrysophyllum* sp. (11 to 8%)]; *Melastomataceae/Combretaceae* (9 to 8%); *Euphorbiaceae* [*Euphorbia* sp. (4 to 2%), and *Croton* sp. (1 to 2%)]; *Vochysiaceae* [*Vochysia* sp. (2%)]; *Arecaceae* (4%); *Chloranthaceae* [*Hedyosmum* sp. (2%)]; *Meliaceae* (2%) and *Sapindaceae* (2 to 3%). The family that represented with less than 1% was *Dilleniaceae* (+). *Poaceae* (9 to 63%) and *Asteraceae* (21 to 7%) are among non-arboreal pollen grains. *Cyperaceae* represented the aquatic plants with 42 to 26%. The $\delta^{13}C$ values ranged from -16.63‰ to -18.37‰, which determine a predominance of C_4 plants;
- Zone II: 13 samples, 60 to 40 cm depth. 60 cm with age of 12,924 cal yr BP, 50 cm with age of 3,831 cal yr BP, 40 cm between 2,534 cal yr BP; between 60 cm and 50 cm, there is a hiatus. The concentration of pollen grains was 65.7 to 487.9 with an average of 312.4 grains of pollen per gram of sediment. Arboreal pollen grains account for 42%; non-arboreal pollen, 50%; indeterminate pollen, 8%; aquatic plants, 26%. Spores accounted for 3%, and fungi,

29 to 15% of total pollen. Arboreal pollen grains identified in the zone are mainly represented by *Apocynaceae* (20 to 6%); *Dillenaceae* [*Tetracera* sp. (1 to 11%), *Curatella americana* (1%)]; *Arecaceae* (7 to 4%); *Melastomataceae/Combretaceae* (7%); *Myrtaceae* (2 to 7%); *Sapotaceae* [*Chrysophyllum* sp. (1 to 3%)]; *Aquifoliaceae* [*Ilex* sp. (1 to 2%)]; *Podocarpaceae* [*Podocarpus* sp. (1%)]; *Fabaceae* [*Copaifera* sp. (1%), *Crudia* sp. (1%) and *Mimosa* sp. (1%)]; *Malvaceae* [*Pseudobombax* sp. (1%)]; *Caryocaraceae* [*Caryocar brasiliense* (1%)]; *Malphigiaceae* [*Byrsonima* sp. (1%)]; *Urticaceae* [*Cecropia* sp. (1%)]; *Vochysiaceae* [*Vochysia* sp. (1%)]; *Bignoniaceae* (1%); *Euphorbiaceae* [*Euphorbia* sp. (1 a 3%), *Croton* sp.(1%), *Sapium* sp. (1%) and *Sebastiania* sp.(1%)], and *Meliaceae* (1%). The family represented with less than 1% was *Anacardiaceae* [*Lithraea sp.* (+)]. Among non-arboreal pollen grains appear *Poaceae* (36 to 30%); *Asteraceae* (3 to 13%); *Lamiaceae* [*Aegiphila* sp. (3%)]; *Amaranthaceae* [*Gomphrena* sp. (1%)], and *Caryophyllaceae* (1%). *Cyperaceae* (24 to 19%) represents the aquatic *taxa*. The $\delta^{13}C$ results showed a ^{13}C enrichment of -22.1‰ to -18.19‰, as a mixture of C_3 and C_4 plants with predominance of C_4 plants;

- Zone III: 10 samples, 40 to 20 cm depth, between 2,364 and 718 yr. The concentration of pollen grains ranged from 488 to 856, with an average of 442 grains of pollen per gram of sediment. Arboreal pollen grains corresponded to 43%; non-arboreal pollen, 51%; indeterminate pollen, 6%; and aquatic *taxa*, 24%. Spores accounted for 8 to 7% and fungi from 36 to 25%. Arboreal pollen grains identified in the zone are represented by *Arecaceae* (21 to 7%); *Apocynaceae* (12 to 5%); *Fabaceae* [*Mimosa* sp. (10 to 2%), *Crudia* sp. (2 to 1%), and *Crotalaria* sp. (1%)]; *Anacardiaceae* [*Lithraea sp.* (15 to 1%) and *Tapirira* sp. (1%)]; *Euphorbiaceae* [*Euphorbia* sp. (8 to 1%), *Alchornea* sp. (2 to 1 %), *Sapium* sp. (3 to 1%), *Croton* sp. (1%), and *Sebastiania* sp. (2 to 1%)]; *Aquifoliaceae* [*Ilex* sp. (2 to 1%)]; *Chloranthaceae* [*Hedyosmum* sp. (1%)]; *Melastomatacea/Combretaceae* (16 to 4%); *Myrtaceae* (4 to 1%); *Urticaceae* [*Cecropia* sp. (3%)]; *Podocarpaceae* [*Podocarpus* sp. (2 to 1%)]; *Sapotaceae* [*Chrysophyllum* sp. (2 to 1%)]; *Bignoniaceae* (1%); *Dilleniaceae* [*Tetracera* sp. (6 to 1%)]; *Verbenaceae* [*Lantana* sp. (1%)], and *Malpighiaceae* (4 to 1%). Non-arboreal pollen grains are represented by *Poaceae* (20 to 57%); *Asteraceae* (23 a 4%); *Amaranthaceae* [*Gomphrena sp* (3 to 1%)]; *Caryophyllaceae* (2 to 1%), and *Xyridaceae* [*Xyris* sp. (3 to 1%)]. Aquatic *taxa* *Cyperaceae* shows 36 to 24%. The $\delta^{13}C$ isotopic results showed ^{13}C enrichment of -22.1‰ to -18.19‰, as a mixture of C_3 and C_4 plants with predominance of C_4 plants;
- Zone IV: 10 samples, 20 to 0 cm depth, the last 718 years. Characterized by the highest pollen concentration of Santa Elisa core, between 856 and 1,787 pollen grains per gram of sediment, and an average of 1,082 pollen grains per gram of sediment, with arboreal pollen (46%), non-arboreal pollen (50%), indeterminate pollen (4%), aquatic *taxa* (17%), spores (6 to 5%), and fungi (36 to 25%). Arboreal pollen grains identified in the zone are represented by *Arecaceae* (21 to 7%); *Fabaceae* [*Copaifera* sp. (3 to 1%), *Crudia* sp. (8 to 1%), *Crotalaria* sp. (2 to 1%), *Mimosa* sp. (7 to 2%) and *Myroxylon* sp. (1%)]; *Anacardiaceae* [*Tapirira* sp. (1%) and *Lithraea sp.* (15 to 7%)]; *Chloranthaceae* [*Hedyosmum* sp. (4 to 1%)]; *Euphorbiaceae* [*Alchornea* sp. (4 to 1 %), *Euphorbia* sp. (2 to 1%), *Sapium* sp. (1%) and *Sebastiania* sp. (2 to 1%)]; *Apocynaceae* (3 to 1%); *Melastomatacea/*

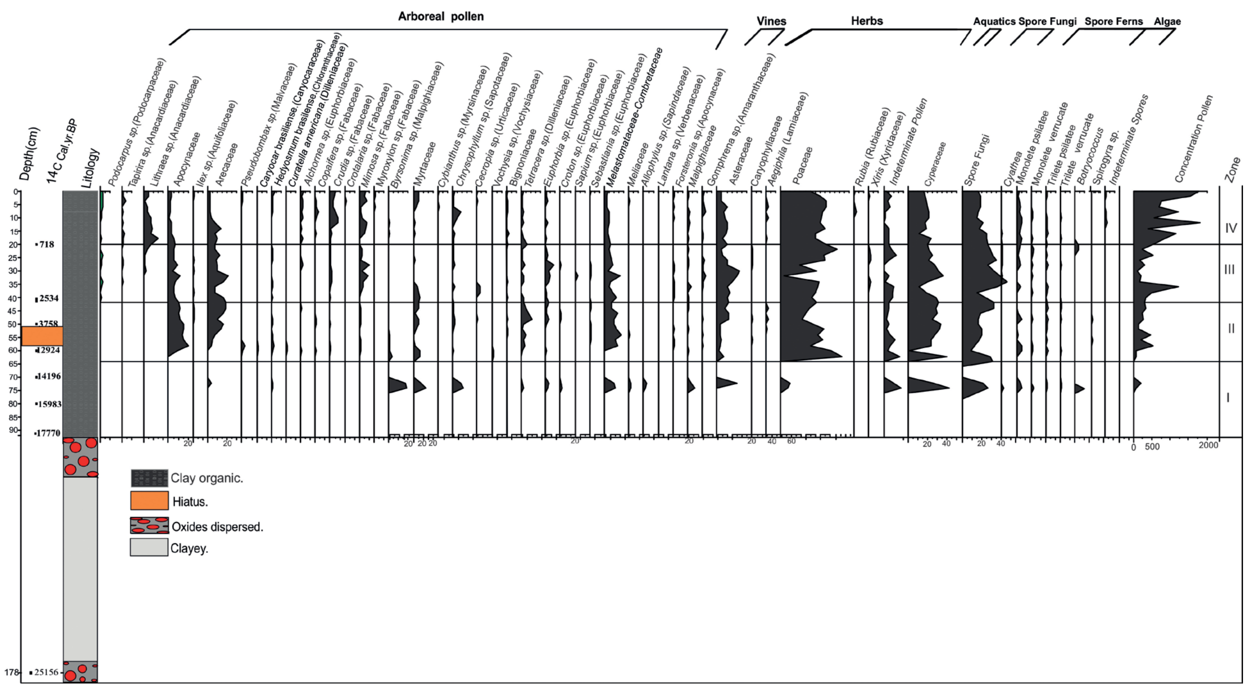

Figure 5. Fossil pollen diagram of Santa Elisa Farm core. Selected pollen and ferns taxa are expressed as percentages of the total sum (except aquatics and ferns) along a depth scale with δ13C, total concentration, AP/NAP and four pollen zones. 14C dates are reported along the depth scale.

Combretaceae (5 to 2%); *Myrtaceae* (6 to 1%); *Sapotaceae* [*Chrysophyllum* sp. (8 to 1%)]; *Podocarpaceae* [*Podocarpus* sp. (3 to 1%)]; *Aquifoliaceae* [*Ilex* sp. (1%)]; *Malvaceae* (*Pseudobombax* sp. 1%); *Malpighiaceae* [*Byrsonima* sp. (1%)]; *Myrsinaceae* [*Cybianthus* sp. (1%)]; *Urticaceae* [*Cecropia* sp. (1%)]; *Vochysiaceae* [*Vochysia* sp. (1%)]; *Bignoniaceae* (1 a 3 %); *Dilleniaceae* [*Tetracera* sp. (3 a 1%)], and *Meliaceae* (1%). The family with less than 1% is *Euphorbiaceae* [*Croton* sp (+)]. Non-arboreal pollen include *Poaceae* (30 to 47%); *Asteraceae* (10 to 4%); *Amaranthaceae* [*Gomphrena sp* (2 to 1%)]; *Xyridaceae* [*Xyris* sp. (1%)], and *Lamiaceae* [*Aegiphila* sp. (3 to 1%)], and aquatic *Cyperaceae* (21 to 11%). The $\delta^{13}C$ isotopic results (-18, 19‰ at -24, 42‰) indicate an impoverishment of $\delta^{13}C$ with predominance of C_3 plants.

DISCUSSION

Modern pollen rain

Considering the studied *taxa* at our site, only *Podocarpaceae* (*Podocarpus* sp.) represents gymnosperms. *Podocarpus* sp., a wind pollinated *taxa*, was not observed in the area of Santa Elisa (Carvalho *et al.* 2013). Its presence in surface sediment samples may be explained as being transported from nearby cities as it is widely used as an ornamental plant.

The pollen grains identified in the modern pollen rain were derived mostly from angiosperms, mainly *Fabaceae, Myrtaceae, Asteraceae, Poaceae, and Cyperaceae*, with a good correspondence between pollen results and botanical surveys (Carvalho *et al.* 2013). The pollen *taxa* with restricted occurrence were *Vochysiaceae*, *Myrsinaceae*, *Euphorbiaceae* (*Sapium* sp. and *Sebastiania* sp.), and *Arecaceae*.

Most of the identified pollen grains represent a broad range of habitats and belong to the physiognomies of Riparian, Cerrado, and Seasonal Semi-deciduous forests (Oliveira-Filho *et al.* 1990, Flora do Brasil 2012, Carvalho *et al.* 2013) with 25 *taxa* (arboreal and non-arboreal) belonging to 20 families. Of these, only 5% have exclusive species to the Riparian Forest physiognomy (Apocynaceae, Arecaceae, Bignoniaceae Myrtaceae, and Malvaceae) observed in surface sediments and in quaternary (core) samples. An exception of *Malvaceae* was not found in core samples. However, *Chloranthaceae* (*Hedyosmum* sp.) associated with Seasonal Semi-deciduous Forest was found in surface, sediment, and core samples.

The remaining 95% represent *taxa* inhabit either in Riparian, Cerrado or in seasonal semi-deciduous forests (*Podocarpaceae*, *Anacardiaceae*, *Amaranthaceae*, *Bignoniaceae*, *Euphorbiaceae*, *Sapotaceae*, *Fabaceae*, *Asteraceae*, *Lamiaceae*), and are in surface and quaternary sediments.

Not surprisingly, as all the samples are located within the forest, the pollen content of surface samples (1, 2, 4 and 5) shows little changes with dominance of arboreal pollen (50%), as seen in Figure 4. Sample 3 demonstrates higher herbaceous *taxa* frequency (81%), due to its proximity to the limit between forest and open field, corresponding to a transition zone or ecotone.

Interpretation of palynological and isotopic results

Results of pollen and isotopic analyses of TOC, N-Total, and $\delta^{13}C$ allow establishing a sequence of changes in vegetation and climate between 25 and 13 kyr BP, and from 4 kyr BP to the present, with a sedimentation gap between 13 and 4 kyr BP.

From 25 to 13 kyr BP

This core basal interval presented clayey sediment and was characterized with evidence of oxidation. Isotopic data indicated low content of TOC and TN with enriched values of $\delta^{13}C$ -15.99‰, suggesting that around 25 kyr BP had a more open vegetation associated with drier climatic conditions than current ones. Dry conditions were not constant recording small cold humidity variations in the area.

Between 25 and 15 kyr BP, $\delta^{13}C$ shows a progressive impoverishment from -15.99‰ to -22.49‰. The values reflect impoverishment associated with a mixture of C_3 and C_4 vegetation (Pessenda *et al.* 2009), suggesting the forest expansion, which is likely related to in water table changes.

Between 15 and 13 kyr, BP, the $\delta^{13}C$ shows a predominance of C_4 plants with values from -19.69‰ to -15.76‰, low TOC content, and low concentration of pollen grains. The dates showed a chronological inversion of 8 kyr BP associated with a regression of the forest vegetation cover, which is likely associated with return to dry climatic conditions.

Ledru (1993) reported similar climatic conditions to this time interval from 15 to 13 kyr BP pollen record for another environment known as Salitre, in Minas Gerais State, around 500 km North in the city of Campinas. In Salitre, between 15 and 12 cal kyr BP, the presence of *Araucaria* sp. and other mixed ombrophilous forest *taxa* (e.g., *Ilex* sp., *Symplocos* sp., and *Drymis* sp.) have been attributed to cool temperature.

At Santa Elisa, we infer water body fluctuations to explain the moisture variability between 25 and 13 kyr BP. Pessenda *et al.* (2009) reinforces occurrences of groundwater level fluctuations in the countryside of São Paulo as a consequence of relative sea level variations. It indicates drier climatic conditions than today. The result is in agreement with other studies (e.g., Ledru *et al.* 1998, Behling 2002), which observed the predominance of dry climate in the South and Southeast Brazil at the late Pleistocene.

Between 13 and 4 kyr BP

The hiatus (Figs. 2 and 5) at 13 and 4 kyr BP found at Santa Elisa was also observed in the Northwest of São Paulo State at JEE, on a river terrace of Mogi Guaçu River (Souza *et al.* 2013). For the JEE record, the gap ranges from 10,192 to 2,183 ^{14}C yr BP, and it is interpreted as an absence of sedimentation or removal of sediments previously deposited by erosion.

At Santa Elisa, absence of sediment deposition may correspond to erosion, due to the fluvial system, a temporal functioning of Quilombo Stream or even drier climatic conditions (Ledru *et al.* 1998).

From 4 cal yr BP to the present

Impoverishment of $\delta^{13}C$ found here may represent forest expansion with a mixture of C_3 and C_4 plants, and predominance of C_3 plants (Pessenda *et al.* 2009). The TOC concentration shows a progressive enrichment due to the interaction between organic matter replacement and decomposition (Pessenda *et al.* 1996). The vegetal tissue deposition justifies high N values on core surface (Pessenda *et al.* 1996).

From 3,700 cal yr BP, a record of *Cecropia* sp. appear at Santa Elisa, which is pioneer *taxa* in secondary forests (Marchant *et al.* 2002). The episode likely happens due to the expansion of Riparian Forest, under warmer and moister climatic conditions. It is in agreement with other pollen records of São Paulo State, in which an increase in moisture rates was observed at 2,189 yr BP for JEE (Souza *et al.* 2013), and at 3,500–1,950 yr BP for Paraíba do Sul River Valley (Garcia *et al.* 2004).

The increase of moisture rates after three kyr BP was also observed in other Brazilian regions, such as Lagoa La Gaiba, North of Pantanal and Eastern Bolivia, where a marked expansion of tropical moist forest after three kyr BP was followed by a dry early-mid Holocene (Whitney *et al.* 2011, Mayle *et al.* 2000).

CONCLUSIONS

Our research provides new paleo data in a poorly studied region. River dynamics and their associated Riparian Forests are very sensitive to water table and climate changes. Pleistocene climatic changes showed differentiated impacts on the ecosystems in São Paulo State, due to their high landscape heterogeneity. The paleo-ecological record of Santa Elisa farm showed drier climatic conditions than current ones and variations in moisture content between 25 and 15 kyr BP. Erosive conditions likely due to drier climatic conditions characterize the late Pleistocene and early Holocene between 13 and 4 kyr BP. The wetter conditions only returned after 4 kyr BP, a general trend for São Paulo State, when climatic conditions relatively like the current ones became fully established.

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