Mid-to-late Holocene vegetation and paleofire dynamics of the last 6,000 years in the Southeast Brazilian highlands montane rainforest

Dinâmica da Vegetação e de Paleoincêndios em Floresta Montana no Holoceno Médio e Tardio (últimos 6.000 Anos), na região serrana do Sudeste do Brasil

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Abstract

The present study aimed to investigate the dynamic of the vegetation and the occurrence of local fires during the Mid-to-Late Holocene in the mountainous domain of the Serra do Mar (SE, Brazil). Investigation involved the analysis of charcoal particles, pollen samples and stable isotopes in colluvial sediment cores, in the upper portion of Macaé River's Basin (Rio de Janeiro State), in order to perceive the environmental changes. Previous studies conducted stable carbon isotope analysis and radiocarbon dating, indicating a timescale within the Mid-to-Late Holocene (last 6,000 cal yrs BP). Two cores were collected for palynological and charcoal particle analyses and the results indicated three significant shifts in the vegetation composition during this period. The analysis indicates that fires played a role in shaping the vegetation dynamics of the montane rainforest. Around 6,000 cal yrs BP, the montane rainforest was predominantly covered by herbaceous-shrub vegetation, characterized by an abundance of grasses and shrubs, along with frequent fires. Between 4,500 and 2,000 cal yrs BP, a transition occurred towards a denser canopy forest with increasing dominance of tree species such as *Ilex*, *Alchornea* and *Machaerium*, accompanied by a decrease in fire activity. Despite forest expansion, fires still occurred and became frequent in the last 900 cal yrs BP, leading to a decrease in tree density and opening of the canopy. Charcoal particles peaks reached maximum levels over the last centuries, being related to local anthropic action.

Keywords: Paleoenvironments, Holocene fires, Brazilian highlands, paleovegetation shifts.

Resumo

O presente estudo tem como objetivo investigar a dinâmica da vegetação e a ocorrência de incêndios locais durante o Holoceno Médio e Tardio no domínio montanhoso da Serra do Mar (SE, Brasil). A investigação envolveu a análise de partículas de carvão, amostras de pólen e isótopos estáveis em testemunhos de sedimentos coluviais, na porção superior da Bacia do Rio Macaé (Estado do Rio de Janeiro), a fim de identificar mudanças paleoambientais. Estudos anteriores conduziram análises de isótopos estáveis e datação por radiocarbono, indicando uma escala de tempo inserida no Holoceno Médio e Tardio (últimos 6.000 anos cal AP). Dois testemunhos foram coletados para análises palinológicas e de partículas de carvão e os resultados indicaram três mudanças significativas na composição da vegetação durante este período. As análises indicam que os incêndios desempenharam um papel de grande influência na dinâmica da vegetação da floresta tropical montana. Por volta de 6.000 anos cal AP, a floresta se misturava com a vegetação herbácea-arbustiva, caracterizada por uma abundância de gramíneas e arbustos com presença de incêndios frequentes. Entre 4.500 e 2.000 anos cal AP, ocorreu uma transição para uma floresta de dossel mais denso, com crescente dominância de espécies de árvores como de Ilex, Alchornea e Machaerium, acompanhada por uma diminuição na atividade de incêndios. Apesar da expansão da floresta, os incêndios ainda ocorreram e se tornaram ainda mais frequentes nos últimos 900 anos cal AP, levando a uma diminuição na densidade de árvores e abertura do dossel. Os picos de partículas de carvão atingiram níveis máximos ao longo dos últimos séculos, sendo relacionados à ação antrópica local.

Palavras-chave: Paleoambientes, Incêndios no Holoceno, Região serrana do Brasil, Mudanças na paleovegetação.

1. Introduction

The climate changes that occurred during the Quaternary in the mountainous domain in southeast Brazil have influenced the vegetation dynamics and fire regimes of the montane rainforests (Behling & Safford 2010, Portes et al. 2020). The reconstruction of local vegetation and fire history in this region, prior to human interference, is crucial for understanding the ecological responses to past climate oscillations and human activities, as well as the projection of future scenarios (Nelle et al. 2010).

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Recent paleoecological studies in the Serra do Mar (highlands of Rio de Janeiro state) mountains have correlated changes in the pattern and dynamics of plant communities and paleofires during the Holocene to drier periods associated with sparse vegetation (Behling & Safford 2010, Portes et al. 2020). Over time, the climatic variations have led to favorable conditions for increased fire frequency and intensity, which in turn have shaped the composition and structure of the montane rainforest (Heyerdahl et al. 2001). Identifying the types of vegetation that contribute to charcoal concentration in paleofire records is crucial for accurately understanding the intricate relationship between fire, vegetation dynamics, human activity, and climate.

Charcoal analysis, along with pollen and isotopic analysis, are valuable technics used for the historical reconstruction of fires (Nelle et al. 2010, Rehn et al. 2022). The analysis of pollen records is a powerful tool for reconstructing past vegetation, identifying periods when burning events occurred by the detection of shifts in the dominant stratum and aftermost vegetation recovery (Whitlock & Anderson 2003). The ability to detect past fire events can be achieved by records in alteration of pollen grain associations, coupled with the observation of carbonized microparticles found alongside the pollen samples (Whitlock & Larsen 2001). In addition to pollen records, the analysis of charcoal particles in sediment cores can provide the frequency and intensity of past fire events (Whitlock & Larsen 2001).

The carbon isotopes analysis has also been utilized to elucidate paleoenvironmental changes in Southern Brazil (Pessenda et al. 1996a). The stable carbon isotope ($\delta^{13}C$) composition in soil organic matter functions as a marker for the presence of C3 and C4 plant species in past plant communities, due to the divergent mechanisms of photosynthesis (Boutton 1996, Jou et al. 2020). The $\delta^{13}C$ values for C3 species (trees) typically fluctuates within the range of -32‰ to -20‰, averaging at -27‰. Conversely, C4 species (grasses) exhibit $\delta^{13}C$ values that lie between -17‰ and -9‰, with an average value of -13‰. Therefore, it is evident that C3 and C4 plant species possess unique $\delta^{13}C$ values, with a difference of approximately 14‰ between them (Boutton 1996, Pessenda et al. 2005).

The research conducted by Behling and Safford (2010) in the Serra dos Órgãos mountains (Rio de Janeiro state) provides evidence that the increase in Poaceae during the Early Holocene contributed to the expansion of herbaceous vegetation. These shifts in vegetation dynamics were likely tied to less humid climatic conditions that persisted until approximately 5,640 cal yrs BP. Additional records from a study by Nehren et al. (2016), conducted in the same highlands, support the hypothesis that from the Late Pleistocene to the Middle Holocene, climatic fluctuations would have induced changes in vegetation at local and regional scales.

The interactions between climate, vegetation, and fire in the Holocene are complex, and research on a more detailed level for the Serra do Mar is necessary to understand the historical changes of the Montane Atlantic rainforest fire prior to documented human occupation. Thus, the present study aimed to investigate the dynamic of the vegetation and the occurrence of local fires during the Mid-to-Late Holocene in the mountainous domain of the Serra do Mar (SE, Brazil), specifically on the upper course of the Macaé de Cima River basin, in the state of Rio de Janeiro, based on geochronological, stable isotopes analysis ($\delta^{13}C$), palynological and charcoal records.

2. Study site and environment setting

The sampling site is located at an altitude of 1,040 m, between 22º19’716”S and 42º16’58 10”W, on a southern slope of the Serra do Mar mountains (locally named Serra de Macaé de Cima), in the Lumiar district of the municipality of Nova Friburgo, in the state of Rio de Janeiro. The stratigraphic section (Boa Vista – SBV) was identified and described by Facadio (2023) as being located on the upper portion of an interfluve that drains into two headwater valleys, which converge into the Boa Vista River, a tributary in the upper course of the Macaé River basin (Fig. 1).

The surface terrain is delineated by a slope predominantly composed of colluvial and talus deposits. This gradient extends in a gentle inclination until it intersects the escarpment of a rocky outcrop, locally referred to as “Pico do Amargosinho”. The upper course of the river basin has a predominance of rugged relief with steep slopes and narrow valleys embedded in different clastic steps (Marçal et al. 2015). In this region, the geomorphological adjustment processes are local, restricted by valley slopes, bedrock erosion and the fluvial reworking of blocks and boulders (Marçal et al. 2017).

The region's soil is mainly composed of Latosols, Cambisols, Neosols, and rocky outcrops (INEA 2014). In general, they are under-developed soils with low fertility that are extremely susceptible to erosion. The rocky substrate mainly consists of crystalline pre-Cambrian granite and gneiss rocks belonging to the São Fidélis unit (Tupinambá et al. 2013, Avelar et al. 2016).

The climate of the upper course of the Macaé River basin is a high-altitude tropical climate. The municipality of Nova Friburgo has the highest values of annual rainfall in the state, reaching 2,500 mm in the highest areas during the summer months from December to February (Coelho Netto et al. 2013). The humid climate conditions in the region and the scarped relief with high topographic gradients favor the predominance of one of the most phytogeographically diverse forest compositions, the Atlantic rainforest (Lima & Guedes-Bruni 1997, INEA 2014).

The study site was originally dominated by dense Ombrophilous Forest (called Atlantic rainforest).

Presently, most of the rainforest patches in SE-Brazil are secondary and remain preserved in protected areas, such as the Serra dos Órgãos National Park - PARNASO in Teresópolis (RJ), and the Environmental Protection Area of Macaé de Cima - APAMC in Nova Friburgo (RJ) (Portes et al. 2020). The composition of the vegetation of this forest is characterized by a relatively dense canopy, with an abundance of fern and palm taxa such as *Euterpe* (Lima & Guedes-Bruni 1997, Bohrer 2021, Bohrer et al. 2021).

3. Materials and methods

3.1 Sediment sampling, AMS ^{14}C dating and δ ^{13}C

The cores from the Boa Vista section are located within a convex slope segment, forming a small divide between two concave axes carved by intermittent channels. Hanging valleys are conditioned by a rocky base level along the Boa Vista stream, situated at 800 meters from the section.

Fig. 2 provides a schematic representation of the cross-sectional profiles of the surveyed site. The surface is covered by an extensive colluvial and talus deposit ramp that gently slopes towards the steep escarpment of a rocky outcrop, locally known as "Pico do Amargosinho" (1,450 m) (Facadio 2023).

The two cores (SBV-A and SBV-B) were extracted for palynological and macroscopic charcoal analyses and were stored in a refrigerated environment (4ºC). The samples from SBV-A were used for palynological analyzes and those from the SBV-B core were used for charcoal samples. The cores (SBV) begin at the base of weathered rocks, and the color description of the material was based on the Munsell color chart (Munsell 1979).

A total of six samples were collected from SBV-A core within fixed interval depths (Table 1), in order to conduct radiocarbon dating. These samples were analyzed in the Accelerator Mass Spectrometry (AMS) at Beta Analytic Inc. testing laboratory in Florida, USA. The ages acquired were converted into conventional calendar age through the Southern Hemisphere calibration curve, SHCal20 (Hogg et al. 2020).

δ^{13}C measurements were conducted on the same six samples used for radiocarbon dating at the Laboratory of Radioecology and Environmental Change (LARA-UFF, Niterói, Brazil) using the EA-IRMS system from Thermo Fisher Scientific Co. Around 1 mg and 4.7 mg of soil in each tin capsule were subjected to analysis. The confidence interval for the samples was established through the materials supplied by the International Atomic Energy Agency (IAEA): Soil (δ^{13}C = -26.66 ± 0.24 VPDB), Caffeine (δ^{13}C = -27.771 ± 0.043 VPDB), Graphite (δ^{13}C = -16.049 ± 0.035 VPDB), and Urea (δ^{13}C = -41.3 ± 0.04 VPDB). For the interpretation of the δ^{13}C values, the intervals between -32 and -22‰ were considered for C3 type plants (Calvin cycle), while the δ^{13}C values between -9 and -17‰ were interpreted as C4 type plants (Boutton 1996, Pessenda et al. 2004).

3.2 Current vegetation

In the Macaé de Cima APA, floristic and phytosociological surveys were conducted to identify plant associations across different physiognomic aspects. This information provides a reference for identifying the past vegetation strata.

In the inventory by Lima & Guedes-Bruni (1997), the families with the greatest species richness included Orchidaceae, Melastomataceae, Rubiaceae, Fabaceae (Leguminosae), Myrtaceae, Bromeliaceae, Lauraceae, Asteraceae, Solanaceae, Piperaceae, and Begoniaceae. More recently, Nunes et al. (2021) identified a similar list of the ten most important families in the Macaé de Cima APA, which comprised Melastomataceae, Myrtaceae, Fabaceae, Asteraceae, Orchidaceae, Rubiaceae, Lauraceae, Bromeliaceae, Solanaceae, and Sapindaceae.

Among the families representing tree species, Melastomataceae, Rubiaceae, Solanaceae, and Asteraceae are the most commonly found on slopes, with most individuals classified as early successional species. In contrast, families such as Myrtaceae, Lauraceae, and Fabaceae are typically associated with environments dominated by more advanced successional stages (Leitão Filho et al. 1987)

In the most humid areas, where dense forest is fully developed, the families Lauraceae, Euphorbiaceae, Palmae, Myrtaceae, and Meliaceae are the most frequent. In preserved forest sections, Nunes et al. (2021) identified Myrtaceae,Lauraceae, Melastomataceae, Rubiaceae, Solanaceae, Fabaceae, Monimiaceae, and Asteraceae as the predominant families.

Within the Pteridophyte group (ferns), most species are epiphytes and are particularly common in the humid montane forests, especially those without a dry season. The families with the highest richness in terms of individual species are Dryopteridaceae, Polypodiaceae, and Cyatheaceae, which are frequently found in the Macaé de Cima region (Sylvestre 1997).

In the disturbed sections, the families Asteraceae, Melastomataceae, Myrtaceae, Sapindaceae, Solanaceae, and Rubiaceae are the most common, with young individuals and small trees being particularly representative (Lima & Guedes-Bruni 1997). According to Nunes et al. (2021), the most important families in the shrub strata include Asteraceae, Arecaceae, Anacardiaceae, Euphorbiaceae, Cyatheaceae, Fabaceae, Melastomataceae, Primulaceae (Myrsinaceae), Rubiaceae, Salicaceae (Flacourtiaceae), and Solanaceae.

According to phytosociological information, the botanical groups were classified as follows: (A) Open Land Vegetation (HS), consisting of associations among herbaceous and shrubby plants; (B) Dense

Rainforest (AR), characterized by associations in exclusively arboreal strata; (C) Wide Distribution (WD), encompassing associations among shrubs and pioneer or generalist trees; and (D) Ferns, which includes various types of ferns.

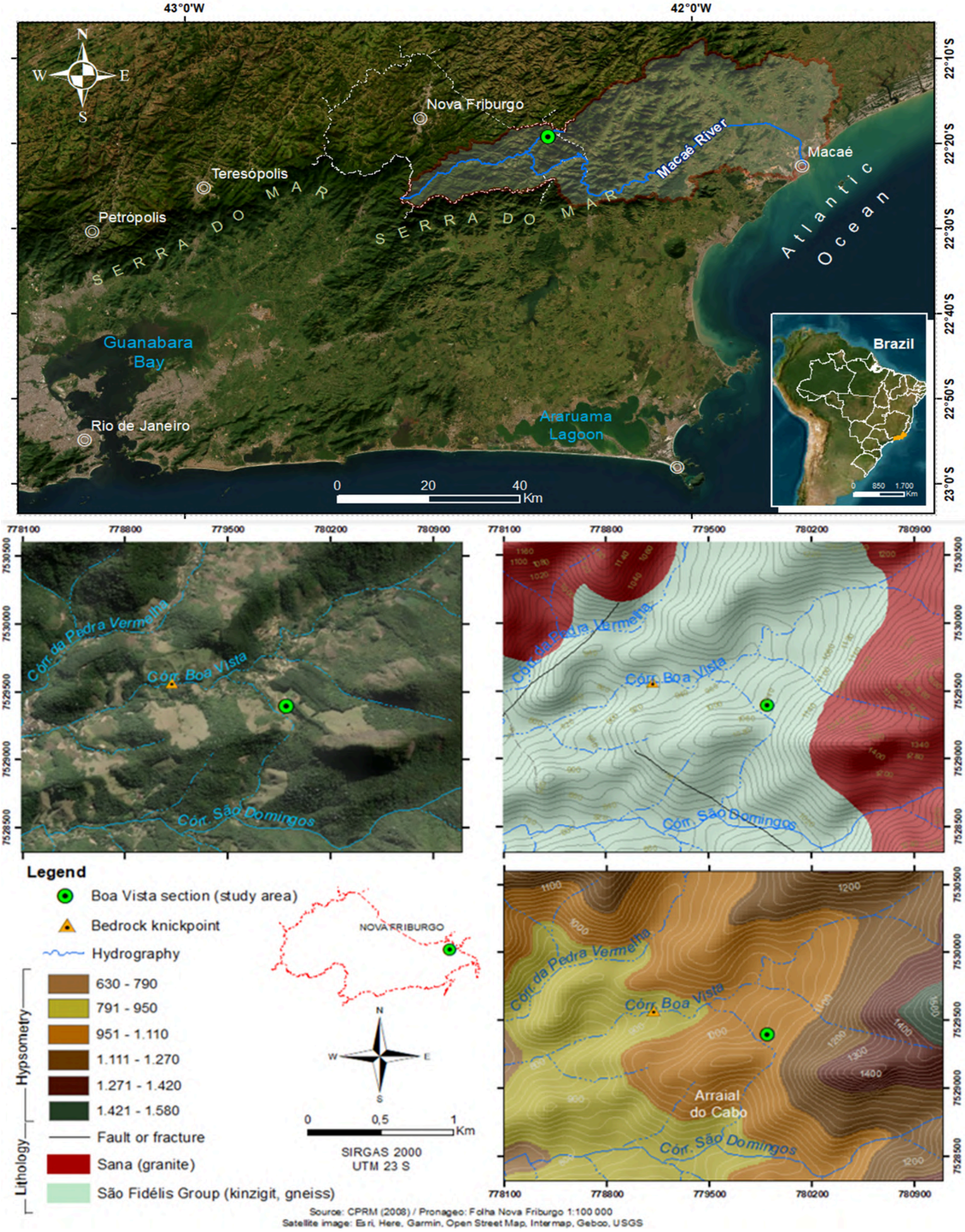

Figure 1 - Location map of the Boa Vista section (SBV), situated on the upper course of the Macaé River basin. This basin drains a large part of the municipality of Nova Friburgo (Rio de Janeiro), at Serra de Macaé de Cima (local name of Serra do Mar).

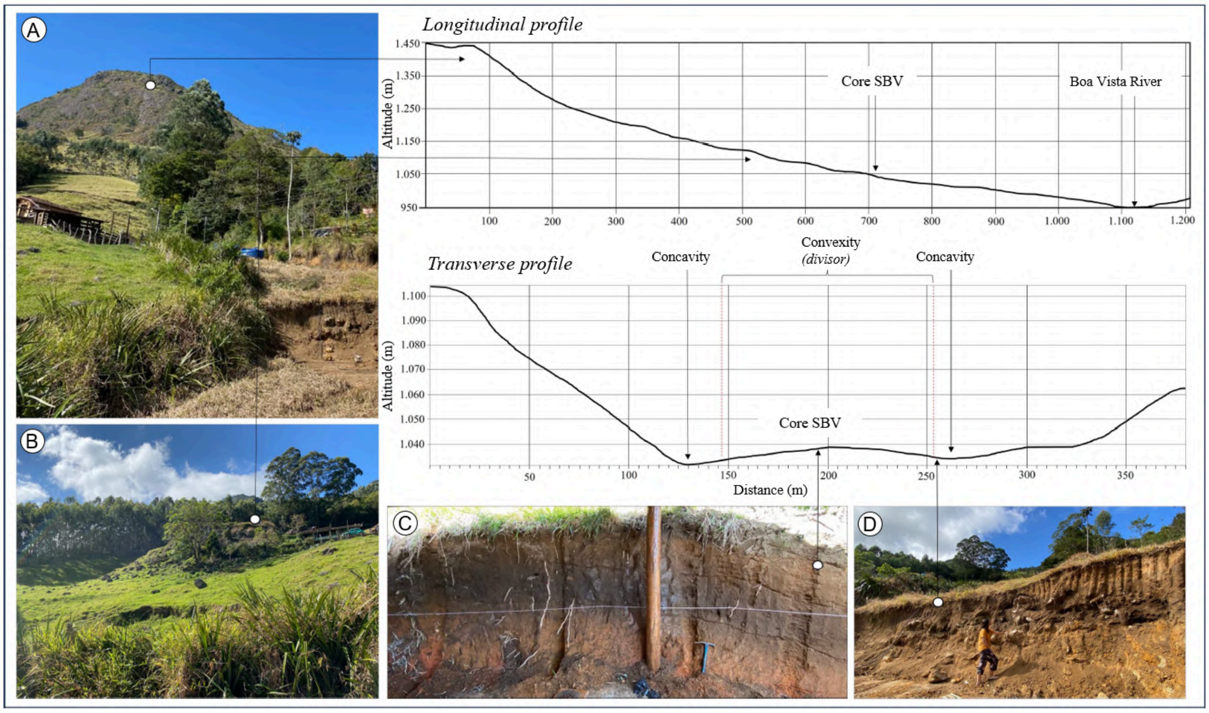

Figure 2 - Core location within the Boa Vista section, Lumiar district, Nova Friburgo (RJ), and longitudinal and transversal profile of the slope, highlighting the convex morphology, forming a small divide between two concavity axes. The photos illustrate the "Pico do Amargosinho," the colluvial and talus deposit, as well as the profile where geochronological survey was conducted (elaborated by Ana Facadio).

3.3 Palynological Analysis

For Quaternary sediments, the manual extraction of cores from exposed stratigraphic profiles allows the reduction of contamination and alteration of the original stratigraphic sequence of the material (Ybert et al., 1992). The collection avoids oxidized material and contamination by modern fungi by cleaning the exposed surface of the profile SBV (Fig. 2.C).

Ten samples were collected at a constant vertical interval of 10 cm, adhering to the maximum distance recommendation between palynological samples as described by Ybert et al., (1992). The samples were packaged in airtight bags (zip-locks), pre-labeled, and stored in a refrigerated environment to preserve the sample content.

The samples were processed according to the classic parameters established by Ybert et al. (1992), which consist of chemical treatment with acids (40% hydrofluoric acid, 10% hydrochloric acid) in a sample of 8 cm^3. This was followed by the standard procedures of Erdtman's (1960) Acetolysis method. Two pastilles of exotic spore marker *Lycopodium clavatum* were added to each sample to determine the pollen grain concentration (Stockmarr 1971). Permanent slides were mounted with glycerinated gelatine and read under an optical microscope.

A minimum of 300 pollen grains were counted in each sample. The pollen grains were also quantified and qualified in regard to the type of deterioration in accordance with the classifications described by Delcourt & Delcourt (1980). Pollen and spore identification was based on pollen catalog references for Brazil (Moore et al. 1997, Melhem et al. 2003, Barreto et al. 2007, Ybert et al. 2016, 2017, 2018, Rossi et al. 2020) and on the reference collection of the Palynology Laboratory of the Federal University of Rio de Janeiro. The nomenclature of the botanical taxa was revised according to the Flora e Funga do Brasil (Jardim Botânico do Rio de Janeiro).

A tabulation was constructed encompassing the pollen grains and spores identified within the SBV-A core specimens. The palynomorph groups were classified in Table 2 according to the phytosociological surveys carried out in Macaé de Cima, Nova Friburgo, Rio de Janeiro, Brazil (Lima & Guedes-Bruni 1997; Coelho et al. 2008, Fraga 2014, Nunes et al. 2021).

The TILIAGRAPH software was employed to statically articulate the data derived from the palynological analyses (Grimm 2011). The pollen data were graphically represented within the software, predicated on the habit of the discerned plants and categorized in accordance with their respective floristic units.

The results generated by this graphical program included percentage and concentration diagrams, displaying representative curves of the collected sediment samples. These diagrams aimed to identify variations in vegetation by highlighting shifts in taxon dominance over the analyzed time interval.

The percentage graphs provide a detailed view of plant formations, while the concentration graphs highlight variations among the defined vegetation groups. Pollen assemblages from the samples were represented in both percentage (%) and concentration (grains/cm³) graphs.

Percentages were calculated based on the total pollen sum, incorporating only identified pollen groups (HS, AR, WD). Other groups, such as ferns, mosses, fungi, and non-pollen palynomorphs, were excluded from these calculations.

3.4 Macrocharcoal Analysis

Macroscopic charcoal analyses (>150 µm) were conducted to investigate the historical fire regime and its potential impact on vegetation. Samples from the SBV-B core were collected at continuous 1 cm intervals throughout the entire core (100 samples).

The process of charcoal formation, as well as the characteristics under which it occurs, is directly influenced by both the temperature of the fire and the duration of combustion (Clark 1988). Furthermore, fire characteristics impact the quantity, size, and deposition patterns of charcoal particles (Finsinger et al. 2014).

In this study, we will make generalized inferences about fire intensity and frequency by quantifying charcoal particles of varying sizes throughout the sediment core, guided by the following main premises: low-intensity fires produce significant charcoal quantities due to incomplete combustion, while frequent low-intensity fires accumulate large amounts of carbonized material (Umbanhowar 1996). In contrast, temperatures above 500ºC lead to minimal charcoal preservation as particles are reduced to ash, and high-intensity fires yield fewer charcoal particles due to rapid combustion (Cope & Chaloner 1985).

In the SBV-B core, the microcharcoal analysis consisted of a quick and low-cost chemical preparation based on the adaptation proposed by Stevenson & Harberle (2005). The chemical preparation of the samples aimed to remove the dark organic material from the sediments to facilitate charcoal fragment identification and differentiation from other types of material (Mustaphi & Pisaric 2014).

Samples from the SBV-B core were collected at continuous 1 cm intervals throughout the entire core. The procedures were carried out, in which 2 cm³ of sediment was treated with hydrogen peroxide (H_2O_2). The wet sieving technique was carried out using a 150 µm mesh. The particles retained in the mesh were then transported to a Petri dish and analyzed under a stereoscopic microscope with a camera and 20x zoom. In order to analyze the charcoal particles, the software CharTool was used, a set of tools for charcoal quantification, designed for use as a set with the Image J program (Snitker 2020). The charcoal particles concentration was calculated and expressed as particles per cm³.

This analysis combined visual protocols with digital methods to assist in charcoal quantification. Charcoal fragments exceeding 150 µm were discerned based on their physical attributes, encompassing a black hue with a silky luster and commendable anatomical preservation. The particulates possess inherent fracture characteristics, which under applied pressure, result in planar and angular fragments (Scott 2010).

The palynological and charcoal results were presented in percentage and concentration diagrams. Data from these analyses were processed using the same software TILIA and TILIAGRAPH, enabling the zoning of pollen assemblages based on the total pollen count and CONISS clustering (Grimm 2011).

4. Results

4.1 AMS ^{14}C dating and δ ^{13}C

The sediment layers were described with colors ranging from yellowish red (5 YR 5/8) to very dark brown (7.5 YR 2.5/2). For the interpretation of the $\delta^{13}C$ values, the intervals between -32 and -22‰ were considered for C3 type plants (Calvin cycle), while the $\delta^{13}C$ values between -9 and -17‰ were interpreted as C4 type plants (Boutton 1996, Pessenda et al. 2004).

The dating results suggest that the local temporal scale for the cores is encompassed within the Middle to Upper Holocene (last 5,939 cal yr BP), as can be observed in Table 1. The obtained dates indicate that the older colluviums were likely transported downstream of the valley, leaving only the more recent deposits intact.

Table 1 – AMS radiocarbon dates of the Boa Vista section (SBV) and carbon stable isotopes ($\delta^{13}C$)

Nº	Lab. code	Depth (cm)	AMS date (^{14}C age BP)	Cal yrs BP SHCAL 20 (95,4%)	Cal yrs BP SHCAL 20 (99,7%)	Mean (µ)	$\delta^{13}C$ (‰)
SBV01	Beta 598861	15	100 ± 0.38 pMC	Modern			- 24,2
SBV03	Beta 598860	35	1,930 ± 30	1,735 - 1,893	1,708 – 1,929	1,821	- 25,8
SBV05	Beta 598859	50	2,640 ± 30	2,700 - 2,782	2,681 – 2,852	2,722	-25,5
SBV07	Beta 598858	70	4,070 ± 30	4,415 - 4,618	4,401 – 4,657	4,510	-24,9
SBV09	Beta 598862	90	5,030 ± 30	5,601 - 5,763	5,597 – 5,898	5,731	-23,6
SBV10	Beta 598857	105	5,160 ± 30	5,842 - 5,939	5,720 – 5,999	5,850	-23,7

4.2 Classification of past vegetation

In the analyzed samples, a total of 23 pollen taxa and 3 spores (ferns) taxa were identified (Tables 2 and 3). Of these, 10 were classified as arboreal, 6 as shrubs, and 6 as herbs. Micrograph prints featuring some of the primary identified pollen types can be found in Fig.s 3 and 4.

The arboreal taxa classified as dense forest (AR) include families such as Apocynaceae, Aquifoliaceae, Araliaceae, Arecaceae, Euphorbiaceae, Fabaceae, Lauraceae, Myrtaceae, Moraceae, and Sapindaceae. The open vegetation (HS), consisting of herbaceous-shrub taxa, includes families such as Amaranthaceae, Asteraceae, Cyperaceae, Iridaceae, Lythraceae, Malvaceae, Poaceae, and Rubiaceae. Lastly, the identified fern taxa (spores) were Polypodiaceae, Aspleniaceae, and Blechnaceae

Table 2 - Botanical taxa of identified palynomorphs according to a phytoecological classification of vegetation in Macaé de Cima, Nova Friburgo (RJ).

Open Land Vegetation / Herbaceous-shrubby (HS)	*Gomphrena* (Amaranthaceae), *Baccharis* (Asteraceae), *Vernonia* (Asteraceae), Cyperaceae, Iridaceae, *Cuphea* (Lythraceae), *Sida (*Malvaceae), Poaceae, *Psychotria* (Rubiaceae), *Borreria* (Rubiaceae), *Alibertia* (Rubiaceae)
Dense Rainforest / Arboreal (AR)	*Peschiera* (Apocynaceae), *Ilex* (Aquifoliaceae), *Schefflera (*Araliaceae), *Euterpe* (Arecaceae), *Alchornea* (Euphorbiaceae), *Machaerium* (Fabaceae), *Nectandra* (Lauraceae), Moraceae, Myrtaceae, *Allophylus* (Sapindaceae)
Wide Distribution (WD)	Euphorbiaceae, *Phyllantus* (Phyllantaceae), Rubiaceae
Ferns	*Polypodium* (Polypodiaceae), Aspleniaceae, *Blechnum* (Blechnaceae), other fern spores

4.3 Palynological and macrocharcoal analysis

IBased on the analyses of the CONISS tool (TILIAGRAPH), three pollen zones were established for the analyzed record (SBV-I, SBV-II e SBV-III). A total of 23 pollen taxa (75,61%) and 3 taxa of ferns spores (24,39%) were identified in the analyzed samples.

The pollen percentage diagram (Fig. 5) illustrates the pollen types in each association group. The summary diagram (Fig. 6) displays the total concentration for each phytophysiognomic group (HS, AR, WD, ferns). Among the total pollen counted (10461 grains/cm³), HS (open land vegetation) is dominant, representing 80.67% with 8439 grains/cm³. This is followed by AR (Dense Tropical Forest) at 11.73% with 1227 grains/cm³, and WD (wide distribution) at 7.60% with 795 grains/cm³.

The summary diagram also highlights the concentration of total intact pollen grains (9170 grains/cm³) and those showing deterioration (1291 grains/cm³). It details the primary types of taphonomic deterioration observed in the analyses: mechanical damage (888 grains/cm³), degradation (322 grains/cm³), and corrosion (81 grains/cm³). Furthermore, it indicates the total charcoal concentration (particles/cm³).

4.3.1 Zone SBV-I (100-65 cm; 5,939-4,618 cal yrs BP)

The SBV-I zone includes the analysis of 4 stratigraphic levels (12 palynological samples). The herbaceous-shrubby vegetation (HS) is dominant with a mean of 87.6%, varying from 82.9% to 94.9%. Poaceae is the dominant taxon with 55.4% (31.6% and 79.4% at 90 cm), followed by Asteraceae, which represents over 13% of the sum total of all the pollen. The highest representation values of this family are of the taxon *Baccharis* with a mean of 25.6% (13.2% - 51.6%). Other taxa that compose the HS group are Cyperaceae 2.2% (0.3% - 4.9%), Malvaceae ~1% (0.5% - 1.4%), and taxa with less than 1% representation, such as Amaranthaceae, Iridaceae, Lythraceae, and Rubiaceae.

Arboreal pollen grains of the Dense Rainforest vegetation group (AR) are rarer at the beginning of the zone (Fig. 5), with a mean presence of arboreal taxa of 7.9%, varying between 3.3% and 12.4%. In this zone, the AR group has its lowest representation value, although it shows growth in the middle of the zone. This group is dominated by common taxa of dense Ombrophilous forest, mainly represented by *Alchornea* with ~2% (1.1% - 3.2%), followed by Moraceae with 1.3% (1% - 1.6%), *Machaerium* with ~1% (0.4% - 2.3%), and other taxa with 1% or less representation, such as Aquifoliaceae, Araliaceae, Arecaceae, Myrtaceae, and Sapindaceae.

The taxa that represent the wide distribution group (WD) also have their lowest representation values among the analyzed zones with 4.6% (1.6% - 7.5%). The dominant family is Euphorbiaceae 2% (~1% - 5.6%), followed by *Phyllanthus* with 1.4% (~1% - 3%), and Rubiaceae with less than 1% representation. Fern spores are also frequent in this zone despite presenting low percentage values with 14.4% (6% - 22.5%). The dominant family in this group is Polypodiaceae with 69.7% (52.1% - 86.3%), followed by Blechnaceae with 8.2% (2% - 12.4%), and Aspleniaceae with 2.7% (1.2% - 5.1%). Other fern spores not identified at the taxonomic level of species were highly representative (14.4%).

This zone had the highest average percentage of intact grains of 82.2% (76.0% - 88.7%), being the zone with the lowest average percentage of deteriorated grains 17.8% (11.3% - 24%). Pollen grains with deterioration through mechanical damage were predominant with a presence of 69.8% (31.4% - 86.2%), followed by degraded grains with 26.2% (10.3% - 65.7%), and damage by corrosion with 4% (2.3% - 7.4%) of representation.

This zone encompasses a 38-level count of sedimentary charcoal (Fig. 6), with an average concentration of charcoal particles of 31 particles/cm³. The concentration of charcoal escalated to its peak at 5,900 cal yrs BP, averaging 101 particles/cm³ (88 – 297 particles/cm³), marking the highest charcoal peak across the analyzed zones.

This concentration then declined until 5,700 cal yrs BP, averaging at 7 particles/cm³ (1 – 21 particles/cm³), signifying the period of the lowest charcoal particle concentration in all three zones. Following this period, the charcoal particle concentration stabilized at an average of 25 particles/cm³ (10 – 40 particles/cm³).

Table 3 - Palynomorphs identified according to a phytoecological classification of vegetation in Macaé de Cima, Nova Friburgo (RJ)

Types of Palynomorphs		Vegetation				Habit			
		HS	AR	WD	Ferns	Herbs	Shrubs	Trees	Variable habit
Pollen	Amaranthaceae (*Gomphrena)*	X				X			
	Apocynaceae (*Peschiera)*		X					X	
	Aquifoliaceae (*Ilex*)		X					X	
	Araliaceae (*Schefflera)*		X					X	
	Arecaceae (*Euterpe)*		X					X	
	Asteraceae (*Baccharis)*	X				X			
	Asteraceae (*Dasyphyllum)*						X		
	Asteraceae (*Vernonia)*	X					X		X
	Cyperaceae	X				X			
	Euphorbiaceae (*Alchornea)*		X					X	
	Euphorbiaceae			X					X
	Fabaceae (*Machaerium)*		X					X	
	Iridaceae	X				X			
	Lauraceae (*Nectandra)*		X					X	
	Lythraceae (*Cuphea)*	X					X		
	Malvaceae (*Sida)*	X					X		
	Moraceae		X						X
	Myrtaceae		X					X	
	Phyllanthaceae (*Phyllanthus)*			X				X	
	Poaceae	X				X			
	Rubiaceae (*Psychotria)*	X					X		
	Rubiaceae			X					X
	Rubiaceae (*Borreria)*	X				X			
	Rubiaceae (*Alibertia)*	X					X		
	Sapindaceae (*Allophylus)*		X					X	
Spores	Polypodiaceae (*Polypodium)*			X					
	Aspleniaceae (*Asplenium)*			X					
	Blechnaceae (*Blechnum*)			X					

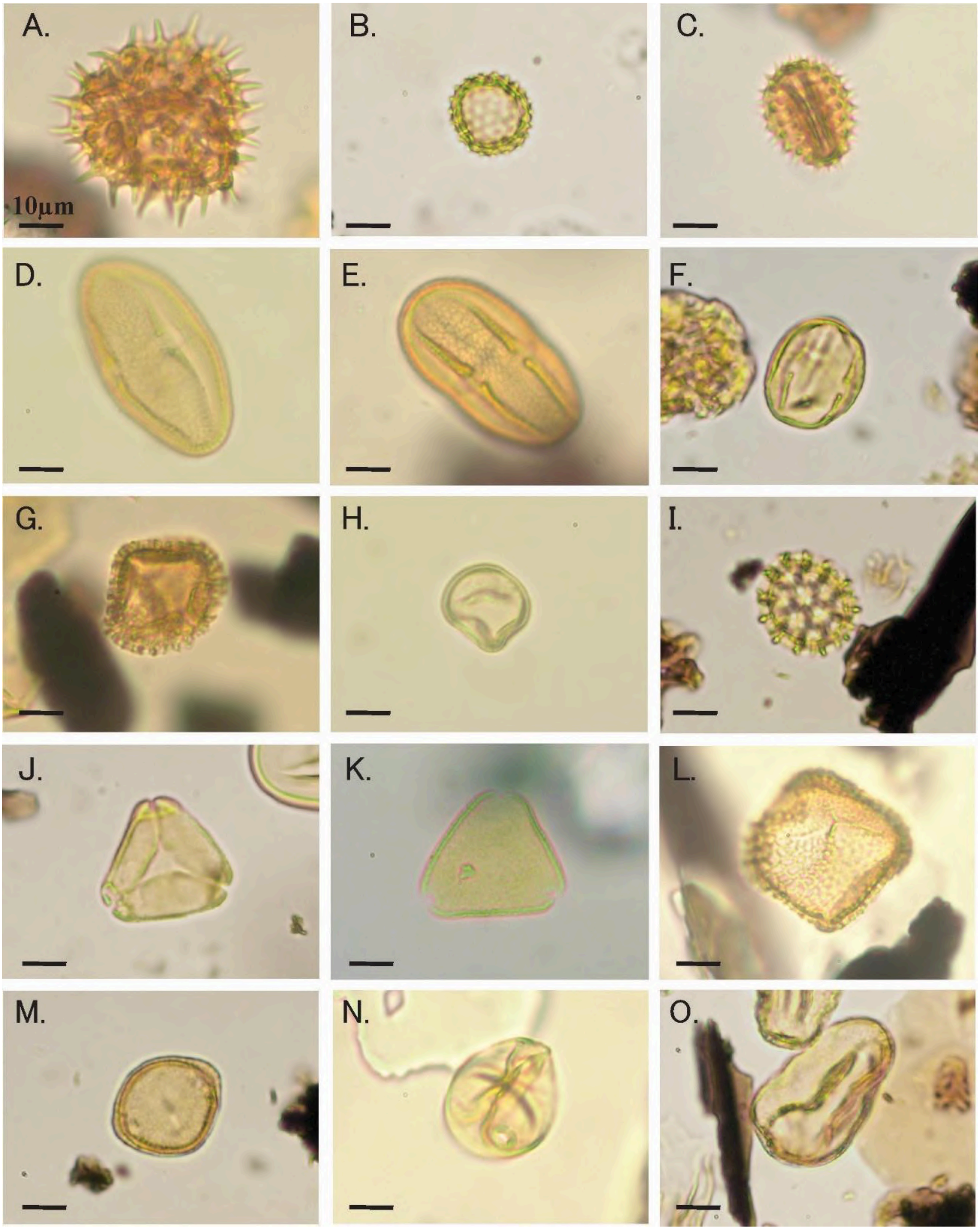

Figure 3 - Some of the main pollen families for the core SBV-A. A-C: Asteraceae, D. Euphorbiaceae, E. Phyllanthaceae, F. Fabaceae, G. Aquifoliaceae, H. Euphorbiaceae, I. Amaranthaceae, J-K: Myrtaceae, L. Araliaceae, M. Moraceae, N. Apocynaceae, O. Cyperaceae. Scale bar: 10μm (40x magnification).

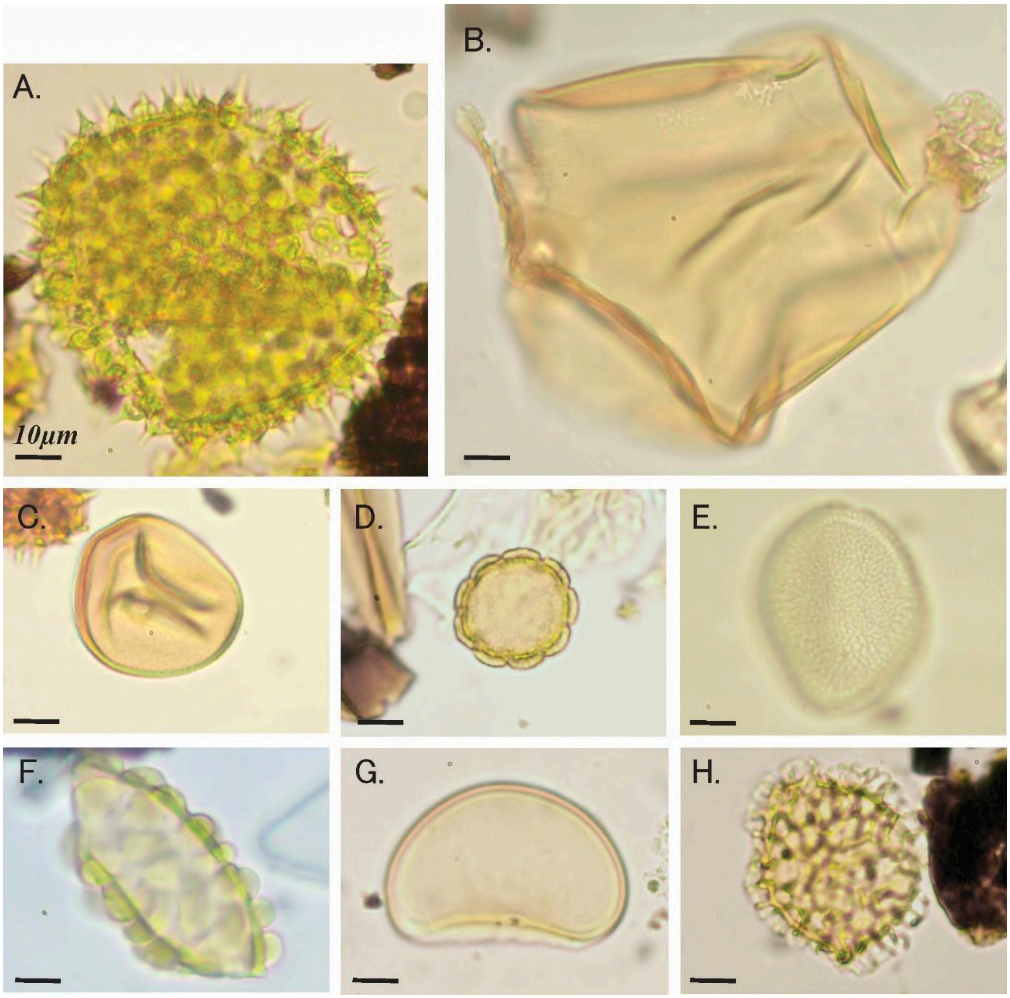

Figure 4 - Some of the main pollen and spores families for the core SBV-A. A. Malvaceae, B-C: Poaceae, D. Rubiaceae, E. Iridaceae, F. Polypodiaceae, G. Blechnaceae, H. Aspleniaceae. Scale bar: 10µm (40x magnification).

4.3.2 Zone SBV-II (65-35 cm; 4,515-1,735 cal yrs BP)

The SBV-II zone is characterized by the analysis of 3 stratigraphic levels (9 palynological samples). Despite the herbaceous-shrubby vegetation (HS) being dominant with a mean of 64%, varying between 52.9% and 71.3%, it presents a decrease in relation to the previous zone (Fig. 5). Poaceae is represented with its lowest percentages of the three zones with 38.4% (26.3% - 45.3%), followed by Asteraceae with 8.7% (8.05% - 9.3%). The Asteraceae family is mainly represented by the taxon *Baccharis* with a mean of 12.2% (9.1% - 16.5%). Other taxa that make up the HS group are similar in all zones and consist of Cyperaceae with 2.2% (0.2% - 4.7%), Malvaceae with 2.2% (0.4% - 4.9%), *Psychotria* with 1.2% (0.1% - 2.2%), and taxa with less than 1% representation such as Amaranthaceae, Iridaceae, Lythraceae, and Rubiaceae.

The arboreal vegetation group (AR) had its highest representation in this zone, with a mean of arboreal taxa of 20.6%, varying between 18.3% and 23.5%. This group is mainly represented by *Alchornea* with 8% (4% - 12.8%), followed by *Machaerium* with 3.8% (1.4% - 6.1%), *Schefflera* with 2.4% (0.5% - 5.6%), Apocynaceae with 2.1% (0.4% - 4.9%), Aquifoliaceae with 1.7% (0.7% - 2.6%), Moraceae with 1.4% (~1% - 2.2%), and other taxa with 1% or less representation such as Myrtaceae, Sapindaceae, and Arecaceae. The taxa that represent the wide distribution group (WD) also have their highest representation value with 15.4% (10.4% - 26.5%). The family Euphorbiaceae (11.1%) is dominant in this group, varying from 6.3% to 19.7%, followed by Rubiaceae with 2.7% (1.9% - 3.3%), and *Phyllanthus* with 1.7% (1.6% - 1.8%).

Similarly, the ferns group has a high representation value with 35% (25.3% - 51.4%). In this group, the family Polypodiaceae is that with the highest representation with 65.1% (60.7% - 67.6%), followed by Blechnaceae with 5.7% (~2% and 9.8%), and Aspleniaceae with 2% (1.7% - 2.2%). Other fern spores not identified at taxonomic level were also notable (27.2%).

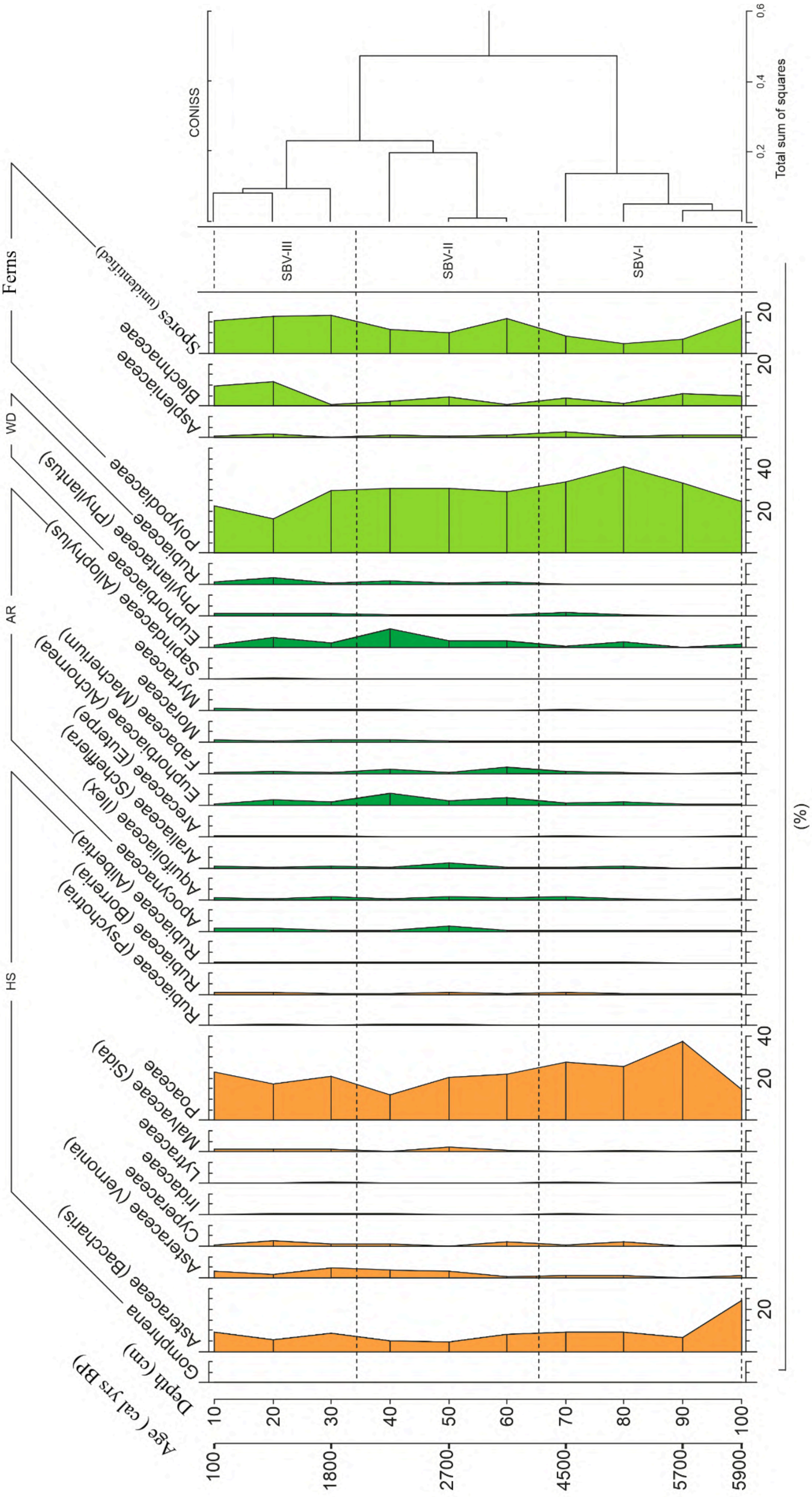

Figure 5 - Diagram of the pollen percentage of the taxa found in the stratigraphic profile of the Boa Vista section (SBV), separated by vegetation.

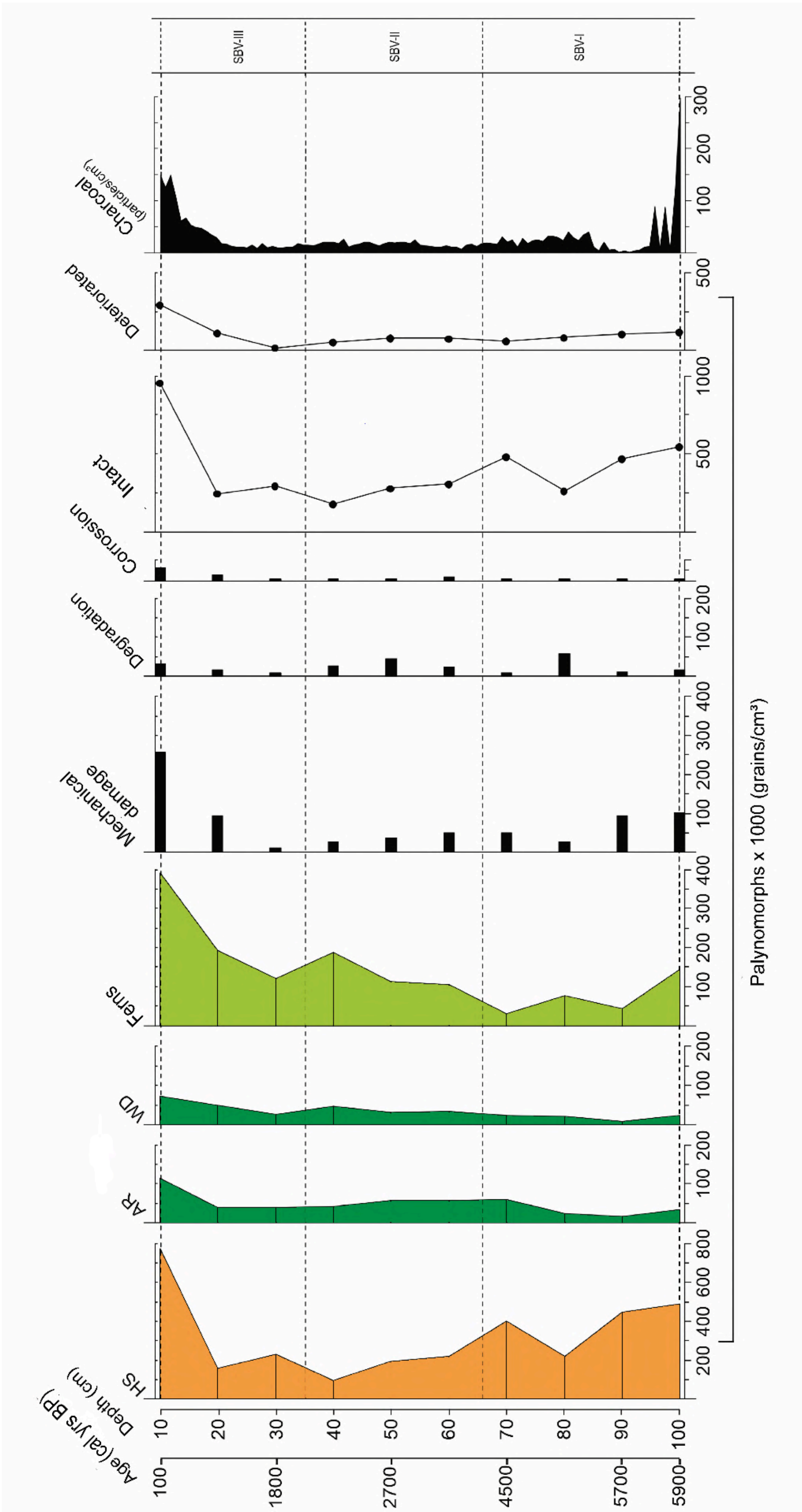

Figure 6 - Diagram of the pollen concentration (grains/cm³) with the ecological groups of the vegetation (HS, AR, WD, ferns), the main types of deterioration found in the pollen grains (mechanical damage, degradation and corrosion), and the concentration of macroscopic particles of charcoal (particles/cm³).

In this zone, the proportions of intact and deteriorated grains showed minimal variation between levels, with intact grains averaging 78.2% (range: 77.0%–80.2%) and deteriorated grains averaging 21.8% (range: 19.8%–23.0%) (Fig. 6). Among the deteriorated grains, those with mechanical damage averaged 50.2% (43.8% - 61.3%), peaking at level 6. Grains damaged due to degradation accounted for 41.5% (29.0% - 50.0%), with the least representation at level 6. Corrosion damage averaged 8.4% (6.3% - 9.7%).

The average charcoal particle concentration is 16 particles/cm³ (ranging from 7 to 26 particles/cm³). Higher charcoal concentrations in this zone were observed briefly at the beginning of the zone (65–55 cm) (Fig. 6), with an average of 13 particles/cm³ (7–17 particles/cm³), and then remained relatively stable, averaging 18 particles/cm³ (12–26 particles/cm³) at the end of the zone.

4.3.3 Zone SBV-III (35-10 cm; 1,893-present cal yrs BP)

The SBV-III zone includes the analysis of 3 stratigraphic levels (9 palynological samples). In Fig. 5, the representation of herbaceous-shrubby vegetation (HS) is high, with an average of 74.5%, varying from 65.5% to 80.4%. Poaceae remains the dominant taxon with 42.5% (36.2% - 48.4%) followed by Asteraceae with 11%, represented with its highest value by the taxon *Baccharis* with 16% (11.3% - 19.5%). Other taxa that make up the HS group are represented by Cyperaceae with 2.8% (1.2% - 5.2%), Malvaceae with 2.2% (2.1% - 2.3%), *Borreria* with 1.3% (0.8% - 1.8%), and Iridaceae with ~1% (0.5% - 1.7%). The taxa with less than 1% representation were Amaranthaceae, Lythraceae, and Rubiaceae.

The arboreal vegetation group (AR) was also present in this zone, with an average of 13.7%, varying between 12% and 16.4%. Among the arboreal taxa, *Alchornea* was the dominant taxon with 3.3% (1% - 5.4%), followed by Apocynaceae with 2% (~1% - 2.5%), Moraceae with 1.8% (1.4% - 2%), Aquifoliaceae with 1.6% (0.5% - 3%), Fabaceae with 1.4% (0.7% - 2.3%), Myrtaceae with 1.3 (~1% - ~2%), and Araliaceae with 1.2% (~1% - 1.4%). Other taxa with 1% or less representation were Sapindaceae and Arecaceae. The arboreal taxa that represent the wide distribution group (WD) had a lower representation value with 12% (7.5% - 20%). The family Euphorbiaceae was dominant with 5.8% (2.9% - 10%), followed by Rubiaceae with 3.6% (1,8% - 6.8%), and *Phyllanthus* with 2.4% (2.2% - 2.7%).

The ferns group was represented by increasing values in this zone of 34% (29,3% - 43,4%). The standout taxon in this group was also Polypodiaceae with 47.4% (34.6% - 61%), followed by Blechnaceae with 15.3% (1.3% - 24.8%), and Aspleniaceae with 1.5% (0.3% - 3.2%). Other ferns spores that were not identified also had high representation values with 35.8% (32.5% - 37.4%).

In this zone, the proportion of intact pollen grains was 79.8% (68.2% - 94.2%) (Fig. 6). The mean proportion of deteriorated pollen grains was 20.2% (5.8% - 31.2%), with the third level exhibiting the highest preservation among all the samples. Among the damaged grains, those with mechanical damage constituted 69.8% (56.3% - 81.5%). The proportion of degraded grains was less significant, averaging 26.2% (10.8% - 37.5%). Corroded grains composed an average of 8.2%, with a range of 6.3% to 10.7%.

4.4 Carbon stable isotopes ($\delta^{13}C$)

All the $\delta^{13}C$ values obtained are within the range of C3 plants (Table 1 and Fig. 7), with values ranging from -25.8 ‰ (35 cm) to -23.6 ‰ (90 cm), indicative of the C3 plant cycle.

In this core, no values corresponding to C4 plants were detected (Fig. 7). However, a decrease in $\delta^{13}C$ values towards the C3 range is noticeable, from 90 cm (-23.6 ‰) at 5,731 cal yrs BP to 35 cm (-25.8 ‰) at 1,821 cal yrs BP. From this depth towards the top of the core, the $\delta^{13}C$ value starts to increase again, reaching -24.2 ‰, corresponding to modern age (100 ± 0.38 pMC).

5. Discussion

Based on the pollen occurrences indicating vegetation types observed in this study, it is suggested that during the Middle Holocene, around 6,000 cal yrs BP, the local vegetation was more open in the Serra de Macaé de Cima, dominated by herbaceous-shrubby taxa, from Poaceae and Asteraceae families. Although the $\delta^{13}C$ signals represent C3 values, variations are observed throughout the core, which may possibly be associated with mixtures of C3 and C4 vegetation responding to changes in climate and fire frequency.

Similar vegetation behavior was found by Portes et al. (2020) in the Serra dos Órgãos. In the study conducted by these authors, the early-to-mid Holocene would have been drier (less humid) compared to the current climate, with dominant taxa representing herbaceous-shrub vegetation. The presence of charcoal in studies on the Serra do Mar and Serra da Mantiqueira Mountain ranges from the end of the Pleistocene to the Holocene, prior to the documented arrival of humans in southeast Brazil, indicate recurrent natural fires (Behling & Lichte 1997, Behling 1997).

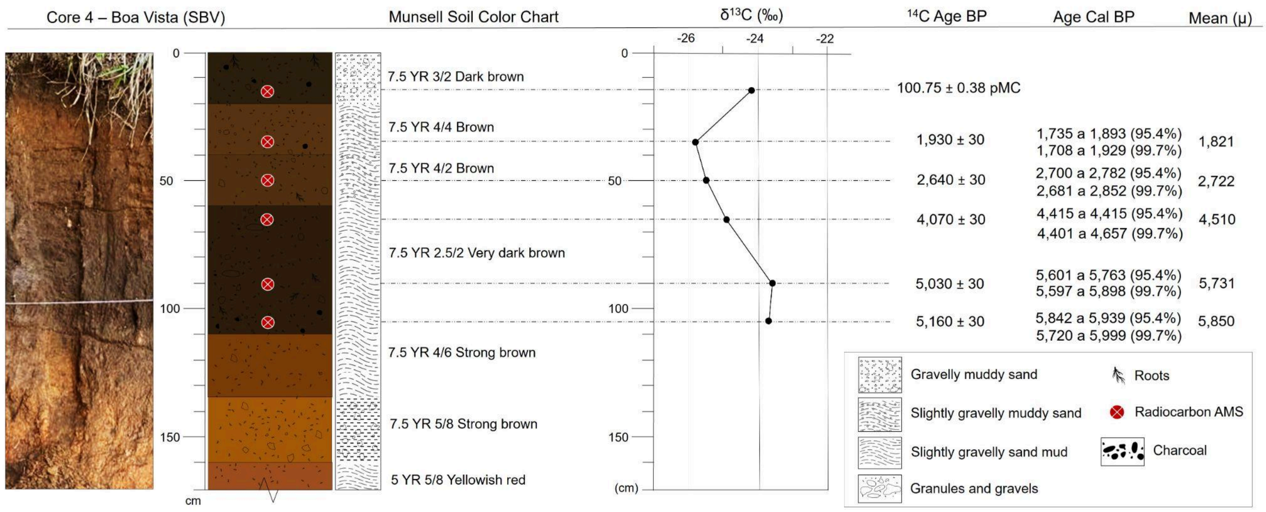

Figure 7 - Profile of the Boa Vista core, with a description of the layer colors, textural classes, stable carbon isotope values ($\delta^{13}C$), and radiocarbon ages (^{14}C).

As in the SBV record, the results found by Behling and Safford (2010) and Portes et al. (2020) indicate that in the transition to the Middle Holocene, the charcoal particle concentrations in the Serra dos Órgãos were also high, with the presence of frequent paleofires. Furthermore, arboreal and fern taxa were rarely present, with a notable reduction in arboreal taxa of wide distribution (WD) at approximately 5,100 cal yrs BP. Large concentrations of pollen grains with mechanical damage can be observed up to 5,100 cal yrs BP, indicating an environment of physical stress to which these grains were subjected.

During the transition to the Late Holocene in the Serra de Macaé de Cima, around 4,600 cal yrs BP, the arboreal taxa become more frequent, with the dominance of *Alchornea* and *Machaerium*, indicating an environmental change to a period of more humid conditions. The analyses suggest that the largest expansion of forest cover, with a strong presence of ferns, occurred around 2,700 cal yrs BP, indicating a progressive transition to more humid climate conditions. Regarding the $\delta^{13}C$ values, humidity increases toward the end of the Middle Holocene and into the Late Holocene, reaching a minimum of -25.8 ‰ at a depth of 35 cm, corresponding to 1,821 cal yrs BP (Fig. 7). For Portes et al. (2020), the climate would have become more humid at around 1,400 cal yrs BP, with the increased representation of forest taxa.

As the climate became even more humid in the last 1,000 cal yrs BP, as indicated by Portes et al. (2020) and Behling et al. (2020), forest taxa with lower diversity came to dominate, which is typical of forests in the initial successional stages. Associated with this, the accentuated increase of the presence of charcoal particles indicated a higher frequency of fire events.

The hypothesis that fire altered the vegetation, impeding the establishment of a more developed forest, is supported by the high presence of *Baccharis* (Asteraceae), which is a species commonly found in the burnt areas of Campos (Boldrini 1997). This species is characterized by benefitting from the disturbance caused by fire and its great capacity for reproduction (Fidelis 2008). A representative timeline scheme based on the analyses of the SBV-A core can be seen in Fig. 8, and it succinctly illustrates the main events upon which the discussions are based.

In the studies carried out by Behling and Safford (2010) on the most recent period in the Serra dos Órgãos, the forest taxa are also more frequent and are represented by a more open forest with the presence of pioneer species of Ilex, Myrtaceae, and Melastomataceae. In the studies by those authors, the herbaceous-shrubby taxa do not suffer alterations, as in the case of those analyzed in the present study. A similar pattern for fires is also observed in the two areas of the Serra do Mar (Serra dos Órgãos e Serra de Macaé de Cima). The fires would have been more frequent, demonstrated by the high concentration of charcoal particles, and this would have impeded the expansion and stability of the forests, even with more humid climate conditions.

Jeske-Pieruschka et al. (2010) point out that the presence of low-diversity forest taxa and charcoal in the same palynological sample could be evidence that fire may be the main cause of alterations to the vegetation. In the Serra de Macaé de Cima, the charcoal particles became even more frequent with the expansion of herbaceous taxa, suggesting that fire was an important factor for the maintenance of herbaceous-shrubby vegetation. In pollen analyses, the strong presence of an herbaceous assemblage in a period of forest taxa may also indicate a poorly advanced successional stage of the vegetation due to degradation by fire (Whitlock & Anderson, 2006).

Thus, even with the presence of charcoal particles throughout the period analyzed in the SBV record, it is observed that in the last 1,000 years, there has been an even more accentuated increase in fire events. This is corroborated by the $\delta^{13}C$ signals, which exhibit enrichment from 35 cm to the top of the core (1,821 cal yrs BP to modern age), potentially indicating a mixture of C3 and C4 plants, even within the C3 plant range. This may suggest a shift toward more open vegetation compared to the previous period, which could be attributed to frequent fires related to changes in land use and cover, as suggested by the dating that spans the modern era. Despite the obtained results indicating possible alterations in the local climate conditions in the last 6,000 cal yrs BP, it is understood that the fire dynamic for these regions may have played a relevant role in the alterations to slope vegetation. Higher resolution studies on these fire events may reveal more detailed information about the spatial patterns and temporal recurrence of these phenomena, their repercussions on vegetation transformations, and the hydroerosive dynamics of slope systems

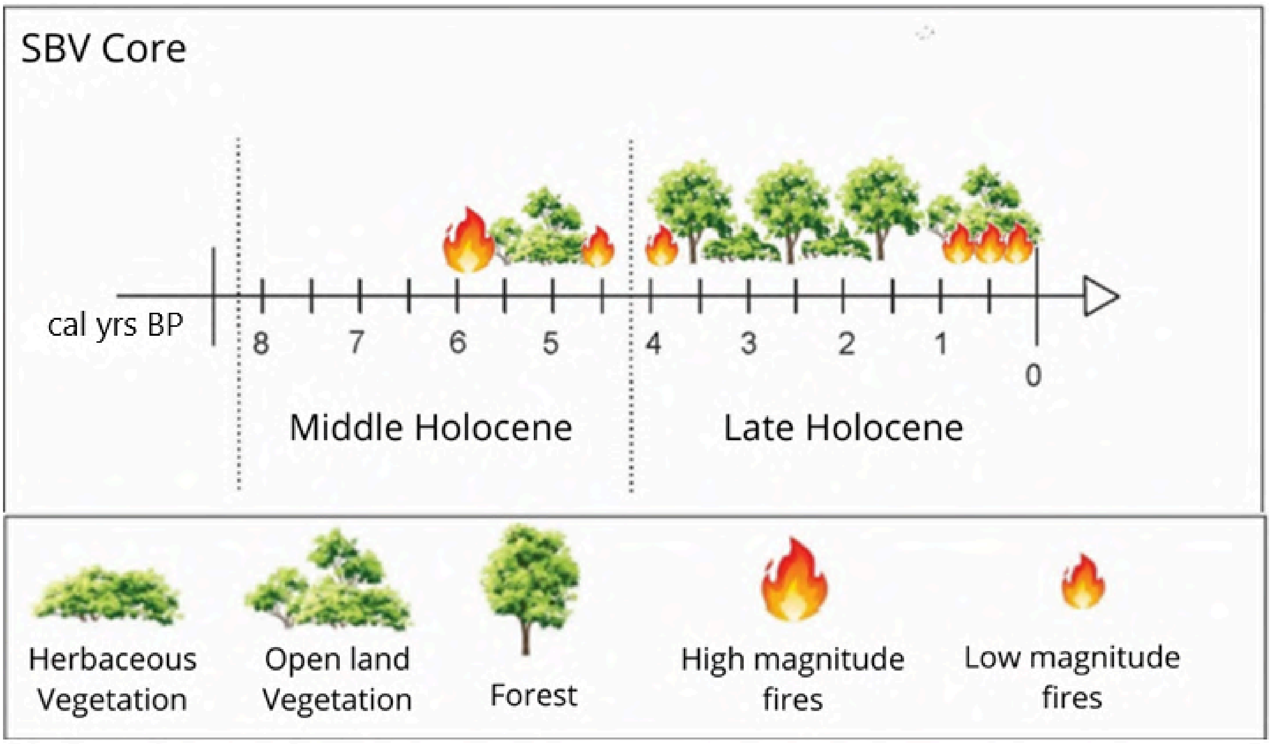

Figure 8 - Illustrative diagram of the chronology derived from the analysis of the SBV-A core sample. The image highlights the temporal occurrences of significant shifts in vegetation cover and fire events, as identified in the study.

6. Conclusions

In the Middle Holocene, in the study area in Serra de Macaé de Cima, around 6,000 cal yrs BP, the climate would have been less humid, with a predominance of herbaceous-shrub vegetation. The arboreal taxa were rare, ferns were less present, and the occurrence of fires was very frequent. In the transition to the Late Holocene, the herbaceous-shrubby vegetation was less present and the arboreal taxa that were rare related to periods of vegetation recovery, in which herbaceous-shrub strata (HS) predominated in initial successional stages.

Approximately 4,500 cal yrs BP, a rise in the diversity of arboreal taxa was observed, concurrent with a reduction in herbaceous-shrub and fern taxa. This trend indicates the evolution of a forest ecosystem that was both denser and more varied in its composition. Notably, during this interval, while fires did occur, their intensity was likely insufficient to cause significant degradation to the vegetation.

At 2,160 cal yrs BP, there was a noted increase in the prevalence of ferns, even with a significant presence of arboreal taxa. This suggests the preservation of forest cover and enhanced environmental stability during this period, potentially linked to more humid weather conditions. In the interval from 1800 to 900 cal yrs BP a dense, but less diverse forest cover persisted. Despite the expansion of the forest, the recurrence of fire events intensified, amplifying the trend towards a more open and less diverse forest, dominated by herbaceous-shrub taxa and ferns.

On the other hand, despite the expansion of the forest signifying a rise in humidity within the climatic conditions, incidents of fire have occurred frequently over the past 900 cal yrs BP. This has amplified the tendency for the forest to become increasingly degraded and less variable. Peaks in charcoal levels have reached great values in recent centuries. Despite being considered the period of greatest humidity, the recurrent presence of fires may have altered the forest vegetation due to diverse processes of ecological succession.

It is projected that this trend will escalate until the end of the century, with an increase in the incidence of fires, presently exacerbated by human interventions, occurring at an average frequency of 350 cases per year in the city of Nova Friburgo (Bolsas 2023). This process signifies an accelerated rate of transformation in forest cover, reverting to the dominance of herbaceous-shrub vegetation.

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Credit author statement

K.M.B.I.: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing-original draft; writing-review&editing.

A.C.F.: Conceptualization; data curation; formal analysis; methodology; validation; visualization; writing-review&editing.

A.L.C.N.: Conceptualization; Resources; funding acquisition; project administration; supervision; validation; visualization; writing-review&editing.

O.M.B.: Conceptualization; data curation; investigation; methodology; resources; supervision; validation; visualization; writing-review&editing.

References

ALMEIDA, J. 2012. Geologia e recursos minerais da Folha Macaé. Belo Horizonte. CPRM.

ALVES, L.M.; CHADWICK, R.; MOISE, A.; BROWN, J.; MARENGO, J.A. 2021. Assessment of rainfall variability and future change in Brazil across multiple timescales. International Journal of Climatology 41, E1875–E1888.

BARRETO, C. F.; LUZ, C. F. P.; BAPTISTA-NETO, J. A.; VILELA, C. G.; BARTH, O. M. 2007. Palynological analysis of a sediment core obtained in Guanabara Bay. 79(2), 223–234.

BARTH, O. M.; BARROS, M. A.; LUZ, C. F. P. 2013. Reconstituição do Bioma Mata Atlântica no Estado do Rio de Janeiro durante o Quaternário através da Palinologia. Em Ismar de Souza Carvalho (Org.), Paleontologia: Cenários de vida – Paleoclimas. Editora Interciência. 1a, Vol. 5, p. 425–444.

BAUERMANN, S. G.; MARQUES-TOIGO, M.; BEHLING, H.; NEVES, P. C. P. 2002. Aspectos tafonômicos em palinologia do Quaternário. Botanica, 52, 223–239.

BEHLING, H. A. 1995. high resolution Holocene pollen record from Lago do Pires, SE Brazil: vegetation, climate and fire history. Journal of Paleolimnology. 14(3), 253–268.

BEHLING, H. 1997. Late Quaternary vegetation, climate and fire history from the tropical mountain region of Morro de Itapeva, SE Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology, 129, 407–422.

BEHLING, H. 2002. South and southeast Brazilian grasslands during Late Quaternary times: a synthesis. Paleogeography, Paleoclimatology, Paleoecology. 177, 19–27.

BEHLING, H.; LICHTE, M. 1997. Evidence of Dry and Cold Climatic Conditions at Glacial Times in Tropical Southeastern Brazil. Quaternary Research, 48, 348-358.

BEHLING, H.; SAFFORD, H. D. 2010. Late-glacial and Holocene vegetation, climate and fire dynamics in the Serra dos Órgãos, Rio de Janeiro State, southeastern Brazil. Global Change Biology, 16(6), 1661–1671.

BIGARELLA, J. J.; MOUSINHO, M. R.; SILVA, J. X. 1965. Processes and environments of the Brazilian Quaternary. VII INQUA, 1–69.

BOUTTON, T. W.; ARCHER, S. R.; MIDWOOD, A. J.; CASAR, I.; NORDT, L. C. 1996. Stable carbon isotope ratios of soil organic matter and their potential use as indicators of palaeoclimate. Em T. W. Boutton & S. Yamasaki (Orgs.), Mass Spectrometry of Soils. Marcel Dekker. p. 47–82.

BOLSAS, L. 2023. Efeitos do fogo na relação chuva-sucção do solo em floresta degradada e gramíneas: subsídios ao estudo de movimentos de massa, Nova Friburgo (RJ). Dissertação de Mestrado, Rio de Janeiro: Universidade Federal do Rio de Janeiro.

CLARK, J. S. 1988. Particle Motion and the Theory of Charcoal Analysis: Source Area, Transport, Deposition, and Sampling. Em Quaternary Research, Vol. 30: 67-80.

CLARK, J. S.; ROYALL, P. D. 1995. Particle-Size evidence for source areas of charcoal accumulation in Late Holocene Sediments of Eastern North American Lakes. Quaternary research, 43, 80–89.

COELHO, L. G., BARTH, O. M., & DE ARAUJO, D. S. D. 2008. Pollen analysis of Holocene sediments from the Poço das Antas National Biological Reserve, Silva Jardim, Rio de Janeiro, Brazil. Anais da Academia Brasileira de Ciências, 531–541.

COELHO NETTO, A. L. 1994. Hidrologia de encosta na interface com a geomorfologia. Em A. J. T. Guerra & S. B. Cunha (Orgs.), Geomorfologia: Uma atualização de bases e conceitos Ed. Bertrand. 2a, p. 93–148.

COELHO NETTO, A. L. 1999. Catastrophic landscape evolution in a humid region (SE Brazil): inheritances from tectonic, climatic and land use induced changes. Suppl. Geogr. Fis. Dinam. Quat., 29(3), 21–48.

COELHO NETTO, A. L.; SATO, A. M.; AVELAR, A. D. S.; VIANNA, L. G. G.; ARAÚJO, I. S.; FERREIRA, D. L. C.; LIMA, P. H.; SILVA, A. P. A.; SILVA, R. P. 2013. January 2011: The extreme landslide disaster in Brazil. Landslide Science and Practice: Risk Assessment, Management and Mitigation, 6, 377–384.

DANTAS, M. E. 2000. Geomorfologia do Estado do Rio de Janeiro (CPRM, Org.). Serviço Geológico do Brasil (CPRM).

DELCOURT, P. A.; DELCOURT, H. R. 1980. Pollen preservation and quaternary environmental history in the Southeastern United States. Palynology, 4(1), 215–231.

ERDTMAN, G. 1960. The Acetolysis Method—A Revised Description. Em The acetolysis method-a revised description. Vol. 54, p. 561–564.

FACADIO, A. C. C. 2023. Mudanças ambientais holocênicas e evolução de encostas no alto curso das bacias dos rios Grande e Macaé, Região Serrana do Rio de Janeiro. [Tese]. Universidade Federal do Rio de Janeiro.

FINSINGER, W.; KELLY, R.; FEVRE, J.; MAGYARI, E. K. 2014. A guide to screening charcoal peaks in macrocharcoal-area records for fire-episode reconstructions. Holocene, 24(8), 1002–1008.

FRAGA, J. S. 2014. Aspectos vegetacionais relevantes à hidrologia de floresta secundária com idades distintas: subsídios à compreensão de estabilidade de encostas [Dissertação]. Universidade Federal do Rio de Janeiro.

FLORA E FUNGA DO BRASIL. Jardim Botânico do Rio de Janeiro. Disponível em:< http://floradobrasil.jbrj.gov.br/ >. Acesso em: 3 Nov 2024

GARDNER, J. J.; WHITLOCK, C. 2001. Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. The Holocene, 11, 541–549.

GUERRA-SOMMER, M.; DEGANI-SCHMIDT, I.; JASPER. A.; BENÍCIO, J. R. W.; CAZZULO-KLEPZIG, M. 2021. Macrocharcoal como indicador de incêndios em turfeiras permianas no Sul da Bacia do Paraná. Contribuições à geologia do Rio Grande do Sul e de Santa Catarina, 273–288.

GRIMM, E.C. 2011. Tilia and Tiliagraph Software1.7.16. Illinois State Museum, Springfield.

HEILBRON, M.; MOHRIAK, W. U.; VALERIANO, C. M.; MILANI, E. J.; ALMEIDA, J.; TUPINAMBÁ, M. 2000. From collision to extension: The roots of the southeasternc ontinentalm argin of Brazil. Em Geophysical Monograph Series. Blackwell Publishing Ltd. Vol. 115, 1–32.

HEYERDAHL, E. K.; BRUBAKER, L. B.; AGEE, J. K. 2001. Spatial controls of historical fire regimes: a multiscale example from the interior west, USA. Ecology. 82(3).

HIRUMA, S. T.; MODENESI-GAUTTIERI, M. C.; RICCOMINI, C. 2013. Late Quaternary colluvial deposits in the Bocaina Plateau, southeastern Brazil highlands: Age and palaeoenvironmental consequences. Boreas, 42(2), 306–316.

HOGG, A. G., HEATON, T. J., HUA, Q., PALMER, J. G., TURNEY, C. S., SOUTHON, J., BAYLISS, A., BLACKWELL, P. G., BOSWIJK, G., RAMSEY, C. B. PEARSON, C., PETCHEY, F., REIMER, P., REIMER, R., AND WACKER, L. 2020. SHCal20 southern hemisphere calibration, 0-55,000 years cal BP, Radiocarbon, 62, 759–778.

INEA - INSTITUTO ESTADUAL DO MEIO AMBIENTE. 2014. APA Estadual de Macaé de Cima: plano de manejo – contextualização e análise regional.

JESKE-PIERUSCHKA, V.; FIDELIS, A.; BERGAMIN, R. S.; VÉLEZ, E.; BEHLING, H. 2010. Araucaria forest dynamics in relation to fire frequency in southern Brazil based on fossil and modern pollen data. Review of Palaeobotany and Palynology, 160(1–2), 53–65.

JOU, R. M.; MACARIO, K. D.; PESSENDA, L. C.; PEREIRA, M. G.; LORENTE, F. L.; PEDROSA, R.; DOS ANJOS, R. M. 2020. The use of carbon isotopes (13C,14C) in different soil types and vegetation coverage in a montane atlantic forest region, Southeast Brazil. Quaternary Geochronology, 101133.

LEITÃO FILHO, H. F. 1987. Considerações sobre a florística de florestas tropicais e subtropicais do Brasil. IPEF, 35, 41–46.

LIMA, H. C.; GUEDES-BRUNI, R. R. 1997. Serra de Macaé de Cima: diversidade florística e conservação em Mata Atlântica. Jardim Botânico do Rio de Janeiro. 1o ed, Vol. 1.

LORSCHEITTER, M. L.; ROTH, L. 2013. O uso da concentração polínica em interpretações paleoambientais. Anuario do Instituto de Geociencias, 36(1), 80–84.

LUZ, C. F. P.; BARTH, O. M.; MARTIN, L. 1999. Evolução das florestas tropical Estacional, Semidecídua e Ombrófila Densa durante o Holoceno Médio na região Norte do Rio de Janeiro, baseada em palinologia. Revista Universidade Guarulhos, 6, 74–84.

LYNCH, J. A.; CLARK, J. S.; STOCKS, B. J. 2004. Charcoal production, dispersal, and deposition from the Fort Providence experimental fire: Interpreting fire regimes from charcoal records in boreal forests. Canadian Journal of Forest Research, 34(8).

MARÇAL, M. S.; RAMOS, R. R. C.; SESSA, J. C.; FEVRIER, P. V. R. 2015. Sedimentação fluvial quaternária no Vale do alto curso do Rio Macaé, Estado do Rio de Janeiro, Brasil. Revista Brasileira de Geomorfologia, vol 16(3), 449-467.

MODENESI, M. C. 1984. Evolução quaternária de uma montanha tropical: o planalto de Campos do Jordão, São Paulo. Rev. Instituto Geológico, 5(112), 7–13.

MODENESI-GAUTTIERI, M. C. 2000. Hillslope deposits and the quaternary evolution of the Altos Campos - Serra da Mantiqueira, from Campos do Jordão to the Itatiaia massif. Revista Brasileira de Geociências, 30(3), 508–514.

MOORE, P. D.; WEBB, J. A.; COLLINSON, M. E.; MOORE, P. D. 1997. Pollen analysis. Blackwell Science.

NEHREN, U.; KIRCHNER, A.; SATTLER, D.; TURETTA, A. P.; HEINRICH, J. 2013. Impact of natural climate change and historical land use on landscape development in the Atlantic Forest of Rio de Janeiro, Brazil. An Acad Bras Cienc, 85(2).

NELLE, O.; DREIBRODT, S.; DANNATH, Y. 2010. Combining pollen and charcoal: Evaluating Holocene vegetation composition and dynamics. Journal of Archaeological Science, 37(9), 2126–2135.

NUNES, M. F. S. Q. C.; ORNELLAS, T.; COLACCHI, F. 2021. A vegetação e flora da APA de Macaé de Cima: ameaças, proteção e manejo. Em G. H. VILLAS BOAS & C. P. MATTOS (Orgs.), 20 anos da Área de Proteção Ambiental de Macaé de Cima: trajetórias e caminhos na pesquisa ambiental. Boa Vista: Editora IOLE/ Rio de Janeiro: EdTur. Vol. 1, p. 263–306.

PAYETTE, S.; DELWAIDE, A.; SCHAFFHAUSER, A.; MAGNAN, G. 2012. Calculating long-term fire frequency at the stand scale from charcoal data. Ecosphere, 3(7).

PESSENDA, L.C.R.; LEDRU, M.P.; GOUVEIA, S.E.M.; ARAVENA, R.; RIBEIRO, A.S.; BENDASSOLLI, J.A.; BOULET, R. 2005. Holocene Paleoenvironmental reconstruction in northeastern Brazil inferred from pollen, charcoal and carbon isotopes records. The Holocene 15(6), 812-820.

PESSENDA, L.C.R.; VALENCIA, E.P.E.; MARTINELLI, L.A; AND CERRI, C.C. 1996. 14C mensurements in tropical soil developed on basic rocks. Radiocarbon 38, 203-08.

PORTES, M. C. G. O.; BEHLING, H.; MONTADE, V.; SAFFORD, H. D. 2020. Holocene vegetation, climate and fire dynamics in the Serra dos Órgãos, Rio de Janeiro State, southeastern Brazil. Acta Palaeobotanica, 60(2), 438–453.

REHN, E., ROWE, C., ULM, S., WOODWARD, C., ZAWADZKI, A., JACOBSEN, G., & BIRD, M. I. 2021. Integrating charcoal morphology and stable carbon isotope analysis to identify non-grass elongate charcoal in tropical savannas. Vegetation History and Archaeobotany. doi:10.1007/s00334-021-00836-z

RHODES, A. N. 1996. Moorland Fire History from Microscopic Charcoal in Soils and Lake Sediments. University of Newcastle.

RIBEIRO, V., GUERRA-SOMMER, M., MENEGAT, R., SIMÕES, J.C., KUHN, L.A., BARBOZA, E.G. AND MARCON, G.T.G. 2024. Pleistocene–Holocene climate events in the southernmost Brazilian internal coastal plain in relation to marine isotopic stages. Journal of South American Earth Sciences, 137, p.104857.

ROSSI, H. R. S.; CORRÊA, A. M. S.; MONTICELLI, C.; MORAIS, L. H.; ROCHA, V. J. 2020. Análise de pólen em pelagem de morcegos Phyllostomidae (Chiroptera) no Parque Estadual Fontes do Ipiranga, São Paulo, SP, Brasil. Hoehnea, vol. 47.

SCOTT, A. C. 2010. Charcoal recognition, taphonomy and uses in palaeoenvironmental analysis. Palaeogeography, Palaeoclimatology, Palaeoecology, 291(1–2), 11–39.

SNITKER, G. 2020. The Charcoal Quantification Tool (CharTool): A Suite of Open-source Tools for Quantifying Charcoal Fragments and Sediment Properties in Archaeological and Paleoecological Analysis. Ethnobiology Letters, 11(1), 103–115.

STEVENSON, J.; HABERLE, S. 2005. Macro Charcoal Analysis: A modified technique used by the Department of Archaeology and Natural History. Papers 5, p. 7.

STOCKMARR, J. 1971. Tablets with Spores used in Absolute Pollen Analysis. Em Pollen et Spores. 13, 615–621.

STOKES, A.; NORRIS, J. E.; VAN BEEK, L. P. H.; BOGAARD, T.; CAMMERAAT, E.; MICKOVSKI, S. B.; JENNER, A.; DI IORIO, A.; FOURCAUD, T. 2008. How vegetation reinforces soil on slopes. Em J. E. Norris, A. Stokes, & S. B. Mickovski (Orgs.), Slope Stability and Erosion Control: Ecotechnological Solutions. Springer, Dordrecht. 1o ed, p. 65–118.

SYLVESTRE, L. S. 1997. Pteridófitas da Reserva Ecológica de Macaé de Cima. Em Serra de Macaé de Cima: Diversidade e Conservação em Mata Atlântica. p. 41–52.

TRAVERS, S. E. 1999. Pollen Performance of Plants in Recently Burned and Unburned Environments. Ecology, 80(7), p. 2427.

TUPINAMBÁ, M.; TEXEIRA, W.; HEILBRON, M. 2013. Evolução Tectônica e Magmática da Faixa Ribeira entre o Neoproterozoico e o Paleozoico Inferior na Região Serrana do Estado do Rio de Janeiro, Brasil. Anuário do Instituto de Geociências - UFRJ, 35_2(1), 140–151.

UMBANHOWAR, C. E. 1996. Recent Fire History of the Northern Great Plains. The American Midland Naturalist, 135(1), 115–121.

UMBANHOWAR, C. E.; MCGRATH, M. J. 1998. Experimental production and analysis of microscopic charcoal from wood, leaves and grasses. Em The Holocene. 8, 341-346.

VELOSO, H. P.; RANGEL FILHO, A. L. R.; LIMA, J. C. A.; IBGE. 1991. Classificação da vegetação brasileira, adaptada a um sistema universal. Ministério da Economia, Fazenda e Planejamento, Fundação Instituto Brasileiro de Geografia e

Estatística, Diretoria de Geociências, Departamento de Recursos Naturais e Estudos Ambientais.
WHITLOCK, C.; ANDERSON, R. S. 2003. Fire History Reconstructions Based on Sediment Records from Lakes and Wetlands. Em Fire and Climatic Change in Temperate Ecosystems of the Western Americas. Springer-Verlag. p. 3–31.
WHITLOCK, C; MILLSPAUGH, S. H. 1996. Testing assumptions of fire history studies: an examination of modern charcoal accumulation in Yellowstone National Park. The Holocene. Vol 6, 7-15.
WHITLOCK, C.; LARSEN, C. 2001. Charcoal as a Fire Proxy. In: J.P. Smol, et al. (eds) Tracking environmental change using lake sediments. Volume 3: Terrestrial, Algal and Siliceous indicators. Dordrecht, Kluwer Academic Publishers. p. 75-97.
YBERT, J. P.; SALGADO-LABOURIAU, M. L.; BARTH, O. M.; LORSCHEITTER, M. L.; BARROS, M. A.; LUZ, C. F. P.; RIBEIRO, M.; SCHEEL, R.; VICENTINI, K. F. 1992. Sugestões para padronização da metodologia empregada em estudos palinológicos do Quaternário. Revista IG, 13(2), 47–49.
YBERT, J.-P.; SCHEEL-YBERT, R.; CARVALHO, M. A. 2016. Grãos de pólen de plantas vasculares dicotiledôneas do Estado do Rio de Janeiro, Brasil Museu Nacional & UFRJ, Orgs. Vol. 1.
YBERT, J.-P.; CARVALHO, M. A.; SCHEEL-YBERT, R. 2017. Grãos de pólen de Plantas vasculares do estado do Rio de Janeiro, Brasil. Museu Nacional & UFRJ, Orgs. 8o ed, Vol. 2.
YBERT, J.-P.; SCHEEL-YBERT, R.; CARVALHO, M. A. 2017. Grãos de pólen de Plantas vasculares do estado do Rio de Janeiro, Brasil. Museu Nacional & UFRJ, Orgs. Vol. 3.
YBERT, J.-P.; CARVALHO, M. A.; SCHEEL-YBERT, R. 2018. Grãos de pólen de Plantas vasculares do estado do Rio de Janeiro, Brasil. Museu Nacional & UFRJ, Orgs. Vol. 4.

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