



*Palaeovegetation and palaeoclimate dynamics during the last 7000 years in the Atlantic forest of Southeastern Brazil based on palynology of a waterlogged sandy soil*

Article

Accepted Version

Creative Commons: Attribution-Noncommercial-No Derivative Works 4.0

Buso Junior, A. A., Pessenda, L. C. R., Mayle, F. E., Lorente, F. L., Volkmer-Ribeiro, C., Schiavo, J. A., Pereira, M. G., Bendassolli, J. A., Macario, K. C. D. and Siqueira, G. S. (2019) Palaeovegetation and palaeoclimate dynamics during the last 7000 years in the Atlantic forest of Southeastern Brazil based on palynology of a waterlogged sandy soil. *Review of Palaeobotany and Palynology*, 264. pp. 1-10. ISSN 0034-6667 doi: <https://doi.org/10.1016/j.revpalbo.2019.02.002> Available at <http://centaur.reading.ac.uk/82348/>

It is advisable to refer to the publisher's version if you intend to cite from the work. See [Guidance on citing](#).

To link to this article DOI: <http://dx.doi.org/10.1016/j.revpalbo.2019.02.002>

Publisher: Elsevier

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the [End User Agreement](#).

[www.reading.ac.uk/centaur](http://www.reading.ac.uk/centaur)

## **CentAUR**

Central Archive at the University of Reading

Reading's research outputs online

1 **Palaeovegetation and palaeoclimate dynamics during the last 7000 years in the**  
2 **Atlantic forest of Southeastern Brazil based on palynology of a waterlogged sandy**  
3 **soil.**

4 BUSO JUNIOR, Antonio Alvaro<sup>(a)</sup>; PESSEDA, Luiz Carlos Ruiz<sup>(a)</sup>; MAYLE, Francis  
5 Edward<sup>(b)</sup>; LORENTE, Flávio Lima<sup>(a)</sup>; VOLKMER-RIBEIRO, Cecília<sup>(c)</sup>; SCHIAVO,  
6 Jolimar Antonio<sup>(d)</sup>; PEREIRA, Marcos Gervasio<sup>(e)</sup>; BENDASSOLLI, José Albertino<sup>(f)</sup>;  
7 MACARIO, Kita Chaves Damasio<sup>(g)</sup>; SIQUEIRA, Geovane Souza<sup>(h)</sup>

8 <sup>(a)</sup>University of São Paulo, <sup>14</sup>C Laboratory, Avenida Centenário 303, 13400-970,  
9 Piracicaba, São Paulo, Brazil

10 <sup>(b)</sup>University of Reading, Centre for Past Climate Change and Department of Geography  
11 & Environmental Science, Reading RG6 6DW, Berkshire, UK

12 <sup>(c)</sup>Fundação Zoobotânica do Rio Grande do Sul, Museu de Ciências Naturais, Rua Dr.  
13 Salvador França 1427, 90690-000, Porto Alegre, Rio Grande do Sul, Brazil

14 <sup>(d)</sup>State University of Mato Grosso do Sul, Unidade Universitária de Aquidauana,  
15 Rodovia Aquidauana, km 12, Aquidauana, Mato Grosso do Sul, Brazil.

16 <sup>(e)</sup>Federal Rural University of Rio de Janeiro, Instituto de Agronomia, Departamento de  
17 Solos, BR-465, Seropédica, Rio de Janeiro, Brazil.

18 <sup>(f)</sup>University of São Paulo, Stable Isotope Laboratory, Avenida Centenário 303, 13400-  
19 970, Piracicaba, São Paulo, Brazil

20 <sup>(g)</sup>Universidade Federal Fluminense, Instituto de Física, Av. General Milton Tavares de  
21 Souza S/N, 24210-346, Niterói, Rio de Janeiro, Brazil

22 <sup>(h)</sup>Vale Nature Reserve, BR 101 Highway, km 122, Linhares, Espírito Santo, Brazil

23 Corresponding author: BUSO JUNIOR, Antonio Alvaro (alvaro.buso.jr@gmail.com)

24

25 Key words: Sandy soil; palynology; continental sponge spicules; C and N stable  
26 isotopes; Holocene; palaeoclimate

27

28 **Abstract**

29 Mineral soils are usually considered inappropriate for pollen analysis because of the  
30 poor quality of pollen and spore preservation and the disturbed stratigraphy. However,  
31 here we present a 57 cm core, collected from a waterlogged sandy soil in the lowland  
32 Atlantic Forest of SE Brazil, which shows good stratigraphy and good preservation of  
33 pollen and spores since ~7000 cal. BP, both in organic and in mineral horizons. By the  
34 other hand, the decomposition of the organic matter and its translocation along the soil  
35 profile led to changes of C and N results (TOC, TN, C/N,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ). Mid-  
36 Holocene palaeoclimate inferences from this study are in accordance with climate  
37 fluctuations presented in previous studies for Central, Southeastern and Southern Brazil,  
38 when a change to more humid climate occurred at ~7000 cal BP. The process  
39 responsible for the presence of biological proxies along this sandy soil profile involves  
40 the continuous deposition of these proxies together with litter and sand, and the  
41 subsequent decomposition of the litter. Ultimately, this process led to the vertical  
42 accretion of the sand with the more resistant organic structures preserved in  
43 stratigraphic sequence. The preservation of pollen and spores along the profile is  
44 probably caused by low pH and redoximorphic conditions due to water saturation. This  
45 study suggests the potential for retrieving useful palaeoecological information from  
46 mineral and organic horizons of tropical waterlogged sandy soils, which is especially  
47 useful for those regions where traditional pollen archives (lakes and peat bogs) are  
48 absent.

49

50 **1. Introduction**

51 1.1 Palynology of mineral soils

52 Mineral soils are generally considered unsuitable for pollen and spore analysis due to  
53 the poor preservation of these microfossils due to oxidation, as well as disturbed  
54 stratigraphy caused by bioturbation and/or pollen translocation down-profile (Dimbleby,  
55 1952; Jacobson and Bradshaw, 1981; Boulet et al., 1995; Davidson et al., 1999).  
56 However, despite these concerns, some mid-high latitude studies have shown that pollen  
57 may be well preserved in some mineral soil profiles (Dimbleby, 1952; Guillet, 1970,  
58 1971a, 1971b; Larocque and Campbell, 1998; Bałaga and Chodorowski, 2006). The  
59 study soil pollen would allow the reconstitution of the local vegetation changes, which  
60 could be related with local vegetation processes and human interferences (Larocque and  
61 Campbell, 1998).

62 1.2 Mid- and late-Holocene climate in Central, Southeastern and Southern Brazil

63 Most pollen studies indicate a change to a wetter climate, beginning ca. 7000-4000  
64 years BP in Central, Southeastern and Southern Brazil (Ledru, 1993; Behling, 1997a,  
65 1997b, 2003; Salgado-Labouriau et al., 1998; Behling and Negrelle, 2001; Garcia et al.,  
66 2004; Pessenda et al., 2009; Veríssimo et al., 2012). Similarly, stable carbon isotopes  
67 from bulk soil organic matter also indicate a transition to wetter conditions in the  
68 middle Holocene in Southeastern Brazil (Gouveia et al., 2002; Pessenda et al., 2004,  
69 Saia et al., 2008).

70 This climate change during mid- to late-Holocene may reflect an intensification of the  
71 austral summer insolation, which led to the strengthening of the South American  
72 Summer Monsoon system (SASM) (Prado et al., 2013). Based on  $\delta^{18}\text{O}$  of speleothems,  
73 Cruz et al. (2005, 2006) showed the increasing importance of the SASM in southern and  
74 southeastern Brazil during the middle to late Holocene.

75 However, pollen data from a lake in the region of the present study (Buso Junior et al.,  
76 2013a) show that humid conditions between 7000 and 4000 cal. BP were followed by  
77 less humid climatic conditions after 4000 cal. BP. The authors attribute this shift to less  
78 humid climatic conditions over the past 4000 yr to the establishment of the modern  
79 seasonal climate in the region, which is influenced by the SASM and marked by a dry  
80 period during the austral winter and a rainy season during the austral summer.

### 81 1.3 Objectives of the study

82 This study aims to test the palaeoenvironmental potential of a waterlogged sandy soil in  
83 the Neotropical forest. We will do this by analysis of pollen, siliceous sponge spicules,  
84 and C and N isotopes from mineral and organic horizons. Because old lakes/bogs are  
85 absent or scarce in many areas of the Neotropical region, the use of waterlogged sandy  
86 soils has the potential for improving understanding of the palaeoenvironmental history  
87 of the Neotropical vegetation.

88

## 89 **2. Study site**

90 Vale Nature Reserve (VNR) is placed at the northern coast of Espírito Santo State,  
91 Southeastern Brazil (Figure 1a, b). It comprises ~25,000 ha of pristine environments in  
92 the Atlantic Forest hotspot.

### 93 2.1 Soils and associated vegetation

94 According to Santos et al. (2004), Oxisols and Ultisols are the most representative soil  
95 orders at VNR, sustaining a dense tropical forest. Spodosols patches covered with  
96 grassland and forest vegetation are interspersed among the Oxisol/Ultisol matrix (Figure  
97 1b). Small patches of Entisols Quartzipsamments are found under *restinga* vegetation.  
98 Wetland soils occur along watercourses, sustaining marshes and swamps.

99 The Oxisols and Ultisols at VNR developed from Neogene sediments of the Barreiras  
100 Formation (Figure 1a) and constitute a flat, smooth undulated terrain, around 20-70 m  
101 above sea level (m a.s.l.) (Moreau et al., 2006; Dominguez, 2009). Oliveira et al. (2010)  
102 studied Spodosols patches in southern Bahia (~120 km north from VNR) and suggested  
103 that Spodosols genesis in the Barreiras Formation is related with clay destruction,  
104 leading to the lateral transformation of Ultisols into Spodosols.

105 The vegetation that overlies Oxisols and Ultisols (*tabuleiros* forest, Figure 1b) is a  
106 relatively tall tropical forest, with the most frequent trees in the Fabaceae, Annonaceae,  
107 Sapotaceae, Rubiaceae, Euphorbiaceae and Bignoniaceae families, constituting a  
108 biologically diverse ecosystem (Peixoto and Gentry, 1990; Thomas, 2003).

109 Grassland and forest vegetation over Spodosols in the Barreiras Formation are  
110 denominated *mussununga* vegetation (Thomas, 2003; Meira Neto et al., 2005; Ferreira  
111 et al., 2014). Some authors denominate the *mussununga* grasslands as *campos nativos*  
112 (native grasslands), nonetheless studies have pointed that differences in structure and  
113 species composition relate with soil physical properties, with grassland *mussunungas*  
114 colonizing areas subjected to water stress (flooding or drying), and savanna and forest  
115 *mussunungas* colonizing mesic areas (Saporetti-Junior et al., 2012).

116 The *restinga* vegetation is a coastal ecosystem occurring on sandy soils (Entisols  
117 Quartzipsamments and Spodosols) along the Brazilian coast. These soils are usually  
118 associated with sand ridges created during marine transgressions and regressions during  
119 the late Pleistocene and middle Holocene (Figure 1a), and some sites may present the  
120 process of podzolization (Oliveira et al., 2010). *Restinga* vegetation patches may present  
121 distinct structures and species composition, reflecting local edaphic and hydrological  
122 conditions (Magnago et al., 2013). Some authors have identified some floristic

123 similarities between *restinga* and *mussunungas* formations, suggestive of edaphic  
124 similarities between these two vegetation types (Ferreira et al., 2014).

## 125 2.2 Climate

126 The SASM controls precipitation patterns at the study site (Garreaud et al., 2009). The  
127 regional climate is strongly seasonal, with the rainy season occurring during the austral  
128 summer. The mean monthly temperature is always higher than 18 °C. The regional  
129 climate (between 1975 and 2002) is classified as the “Aw” type in the Köppen system,  
130 with mean annual precipitation of 1215 mm, mean annual temperature of 23.3 °C, and a  
131 dry season during the June-September winter months (Buso Junior et al., 2013a).

## 132 2.3 Sampling site

133 The Nativo do Flamengo sampling site (NF – 19°09’48.6’’S, 39°56’22.3’’W, ~25 m  
134 a.s.l.) is a circular, peat-covered wetland depression, ~100 m in diameter, occurring  
135 inside a plain area of deep Spodosol.

136 The Spodosol around NF is covered by a mussununga forest (Figure 1b, c) and,  
137 according to Santos et al. (2004), presents a thin layer (2 cm) of litter overlying the grey  
138 sand of the A horizon (8 cm thick) followed by a thick leached and white E horizon,  
139 with the spodic B horizon appearing at 171 cm depth.

140 During the dry season, NF usually lacks surface water but nonetheless has a shallow  
141 water table immediately below the peat layer and is characterized as a waterlogged  
142 place. Because of the groundwater influence, it was not possible to dig a trench in the  
143 study site to proceed with the substrate description, analysis and classification.

144 Remnants of *Salvinia* sp. and dried specimens of the freshwater sponge  
145 *Anheteromeyenia vitrea* at the bog surface are indicative of short-term flooding events,  
146 even during the dry season. The wetland is densely colonized by Cyperaceae species  
147 (e.g. *Cyperus distatus* and *Fuirena umbellata*), and scattered trees and shrubs grow



148 across the site and around its margins, including *Ocotea pulchella* (Lauraceae),  
149 *Tibouchina urceolaris* (Melastomataceae), *Myrsine rubra* (Myrsinaceae),  
150 *Campomanesia* sp. (Myrtaceae) and *Aeschynomene fluminensis* (Fabaceae).  
151 *Paepalanthus tortilis* (Eriocaulaceae), Poaceae and Bromeliaceae are common herbs.

152

### 153 **3. Materials and methods**

154 A 57 cm soil core was collected from the NF site with a 7-cm diameter aluminium  
155 cylinder. The core was X-rayed, split longitudinally and cut into two centimetres  
156 increments. Selected samples were analysed for:  $^{14}\text{C}$  dating, C and N elemental and  
157 isotopic composition, grain size distribution, soil pH, and biological proxies (pollen,  
158 spores, and freshwater sponge spicules). This multiproxy approach was undertaken to  
159 determine the full potential of waterlogged sandy soil as an archive for  
160 palaeoenvironmental reconstruction – pollen for vegetation history, C and N analyses to  
161 determine the origin of organic matter in reduced environments (Table 1), and  
162 freshwater sponge spicules to determine local hydrological changes.

#### 163 3.1 $^{14}\text{C}$ dating

164 Five samples were selected for  $^{14}\text{C}$  dating. Pre-treatments included the removal of  
165 modern roots fragments and cold/hot hydrolysis with diluted HCl (Table 2). The  
166 hydrolysis of peat samples (11-13 cm and 05-07 cm) was more aggressive than the  
167 hydrolysis of sandy and friable samples (21-23 cm, 47-49 cm and 49-51 cm). Samples  
168 were combusted at the  $^{14}\text{C}$  Laboratory, and the purified  $\text{CO}_2$  was sent to the University  
169 of Georgia, USA, or to the LACUFF Laboratory, Brazil, for accelerator mass  
170 spectrometry (AMS) dating. For pre-Bomb samples, ages are expressed as years before  
171 present (BP) and calibrated ages (cal. BP,  $2\sigma$ ), according to the SHCal13 curve (Hogg et  
172 al., 2013), using the software CALIB Rev 7.0.4 (Stuiver and Reimer, 1993) for  $^{14}\text{C}$  age

173 calibration. For post-bomb samples,  $^{14}\text{C}$  activity was expressed as the percentage of  
174 modern carbon (pMC), while calibrated ages were expressed as cal. AD,  $2\sigma$ , according  
175 to the Brazil curve (Santos et al., 2015) and the CALIBomb software  
176 (<http://calib.org/CALIBomb/>). Calibrated ages were used to create an age model in the  
177 software Tilia 1.7.16 (Grimm, 1992) to interpolate ages at any undated interval in the  
178 core.

### 179 3.2 C and N analyses

180 Modern root fragments were manually removed from samples selected for C and N  
181 analyses. Mineral samples were sieved (350  $\mu\text{m}$ ) with distilled water to remove coarse  
182 sand grains. All samples were dried at 50  $^{\circ}\text{C}$ . Analyses were carried out at the Stable  
183 Isotope Laboratory (CENA/USP) using an elemental analyzer attached to an ANCA SL  
184 2020 mass spectrometer. Total organic C (TOC) and total N (TN) are expressed as  
185 percentage of dry weight, with an analytical precision of 0.09% and 0.07%,  
186 respectively. Stable isotopes ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ) were measured with respect to VPDB and  
187 atmospheric N as standards, respectively, and are expressed as *per mil* (‰) with a  
188 standard deviation of 0.2‰.

### 189 3.3 Grain size

190 *In natura* samples were sieved (mesh = 1 mm) using distilled water, and the dry mass  
191 ratio of the mineral fraction > 1 mm was calculated in relation to the original mass of *in*  
192 *natura* samples. Grain size distribution of the fraction < 1 mm was determined by laser  
193 diffraction analysis. Samples were processed using  $\text{H}_2\text{O}_2$  to eliminate organic matter  
194 and HCl to eliminate carbonates. Grain size distributions of the fraction < 1 mm were  
195 divided into sand (1-0.0625 mm), silt (62.5-3.9  $\mu\text{m}$ ) and clay (3.9-0.12  $\mu\text{m}$ ), following  
196 Wentworth (1922).

### 197 3.4 Soil pH

198 Five intervals were selected for the determination of pH in water and in KCl 1 mol.L<sup>-1</sup> (  
199 in weight soil: solution = 1:2.5) by means of a potentiometer (Teixeira et al., 2017).  
200 3.5 Biological proxies

201 A qualitative analysis of siliceous sponge spicules was carried out in 6 samples. To  
202 remove organic matter, samples were treated with H<sub>2</sub>O<sub>2</sub> at 50 °C, and washed with  
203 distilled water. Subsequently, samples were treated with 10% HCl, at 50 °C for 10  
204 minutes, and washed in distilled water. Residues were stored in distilled water and then  
205 mounted on light microscope slides with Naphrax or Entellan. Sponge taxa  
206 (gemmoscleres and microscleres) were identified using the following references:  
207 Tavares et al. (2003), Volkmer-Ribeiro et al. (2006), Volkmer-Ribeiro and Machado  
208 (2007) and Buso Junior et al. (2012).

209 Pollen and spore analysis was carried out on 11 samples of 2 cm<sup>3</sup>. Samples were sieved  
210 (350 µm) with 5% KOH for removal of coarse sand and coarse vegetal fragments. They  
211 were processed according to Colinvaux et al. (1999), with the addition of exotic  
212 *Lycopodium* spores to determine pollen and spore concentrations, dissolution of silica  
213 with HF, and removal of organic matter with 5% KOH and acetolysis. Residues were  
214 mounted on light microscope slides using liquid glycerin as the mounting medium. For  
215 each sample, at least 200 tree or shrub pollen grains were counted in at least 3 slides.  
216 The total terrestrial pollen sum includes trees, shrubs, terrestrial herbs and  
217 indeterminate/reworked pollen grains, and is the basis for calculation of percentages.  
218 Identification was based on the pollen reference collection of the CENA/USP <sup>14</sup>C  
219 Laboratory, which contains more than 1500 samples of the regional vegetation, and on  
220 Lorente et al. (2017). Tilia 1.7.16 software (Grimm, 1992) was used to construct pollen  
221 and spore diagrams. CONISS software (Grimm, 1987) was used for constrained cluster  
222 analysis to produce pollen assemblage zones.

223

## 224 **4. Results and discussion**

### 225 4.1 Core description, grain size distribution and soil pH

226 The X-ray image allows differentiation of mineral and organic intervals in the NF core.  
227 Furthermore, the X-ray image evidences the absence of sedimentary structures and  
228 stratification (Figure 2), indicating that some of the changes in the content and in the  
229 characteristics of the organic matter in NF core are originated from post-depositional  
230 processes related with pedogenesis. Both mineral and organic intervals present low pH  
231 in H<sub>2</sub>O (4.5 to 5.7), moreover pH values in KCl (3.2 to 3.9) are always lower than in  
232 H<sub>2</sub>O (Table 3). These pH values are in agreement with studies in Spodosols of the  
233 Barreiras Formation, reflecting the acid characteristic and the predominance of negative  
234 charges in these soils (Oliveira et al., 2010; Secretti, 2013).

235 The mineral interval (57-17 cm depth) is composed predominantly of sand (Figure 2),  
236 and may be subdivided into five sub-intervals based upon gradations of grayscale: (i)  
237 from 57-52 cm, hardened and dark brownish-grey sand with some silt; (ii) from 52 to 48  
238 cm, dark grey, friable sand; (iii) from 48 to 35 cm, light grey, friable sand; (iv) from 35  
239 to 21 cm, dark grey, friable sand; (v) from 21 to 17 cm, black and friable sand.

240 The organic interval (17 to -5 cm) is composed of organic matter (17-00 cm) and  
241 modern litter (0 to -5 cm). The humus layer contains decomposed organic matter,  
242 *Salvinia* microsporangia, lots of modern roots and some sand. We attribute the presence  
243 of sand in the organic interval to the surface transport of sand grains from the  
244 surrounding *mussununga* forest by water runoff, as proposed by Calegari et al. (2017),  
245 based on a study of soil phytoliths at the NF site.

246 The presence of peat from 17 to -5 cm is the result of the accumulation of litter,  
247 reflecting vegetation productivity, relatively low organic matter decomposition, caused

248 by anoxic conditions that prevail during the rainy season, and low pH, which decreases  
249 the rate of decomposition (van Breemen and Buurman, 1998).

250 Conversely, the stratification of the carbon-enriched layers (litter – humus – black  
251 friable sand) reflects decay processes that lead to the incorporation of the organic matter  
252 into the mineral interval (Ejsackers and Zehnder, 1990). According to Melillo et al.  
253 (1989), the below-ground decomposition of the organic matter is influenced mainly by  
254 environmental factors such as temperature, moisture and soil texture. At the study site,  
255 decomposition rates are probably low, nonetheless these rates may be enhanced by oxic  
256 conditions during the dry season, causing decomposition of the organic matter and its  
257 incorporation into the mineral interval.

258 Macroscopic characteristics of NF core presented above differs markedly from the  
259 description of the deep Spodosol patch that occurs around NF site (Subsection 2.3).

260 Similar situation was found by Dubroeuq and Volkoff (1998) in Podzolic plains in  
261 northern Amazonia. The authors suggested that small patches of waterlogged shallow  
262 Spodosols with peat occurring in the middle of deep Spodosol areas would have  
263 evolved in response to the rise of the groundwater level. In this sense, the onset of  
264 wetter climate led to the gradual development of peat on the surface, as well as the  
265 development of a secondary argillic horizon within the E horizon of the deep Spodosol.

266 Furthermore, according to Dubroeuq and Volkoff (1998), under these conditions the  
267 dissolution of quartz increases, leading to the lowering of the relief. This model may  
268 help to explain the differences observed between NF profile and the surrounding deep  
269 Spodosol, especially in relation to the lowered relief of the site, the presence of peat on  
270 the surface and the hardened and dark interval from 57 to 52 cm depth. Moreover, if  
271 such mechanism occurred in NF site, probably a wetter climate event may be associated  
272 with it and will be discussed later (Subsections 4.5 and 4.6).

273

#### 274 4.2 <sup>14</sup>C dating

275 AMS dates ranged from 6672 cal. BP at 47-49 cm to 1852 cal. BP at 21-23 cm and

276 modern ages at 11-13 and 05-07 cm (Table 2). The two lowermost dated samples

277 showed age inversions, which can not be attributed to differences regarding <sup>14</sup>C

278 measurements because both LACUFF and UGAMS laboratories were recently

279 intercompared and showed very good agreement for all data sets (Macario et al., 2013).

280 The age inversion may be due to the distinct treatments of these two samples and

281 distinct clay contents. Due to the low availability of sample mass, the acid pre-treatment

282 of sample 47-49 cm was more aggressive (60 °C, 1h hydrolysis, Table 2) than that

283 applied to sample 49-51 cm (hydrolysis at room temperature), probably resulting in a

284 more efficient removal of fulvic acids and, consequently, an older age for sample 47-49

285 cm. According to Scharpenseel and Becker-Heidmann (1992), clay organic complexes

286 have lower tendency towards rejuvenation of the soil organic matter. Consequently, a

287 concurrent cause of the age inversion is the higher content of organomineral complexes

288 in sample 47-49 cm, which presents a higher clay content than sample 49-51 cm (17%

289 and 9%, respectively).

290 According to Melillo et al. (1989) and Ejsackers and Zehnder (1990), less than 20% of

291 organic matter remains after four years of litter deposition. Consequently, AMS ages

292 obtained for the organic interval probably reflect both the fast organic matter deposition

293 and the fast decay dynamics at the organic layer. Ages obtained for the upper humus

294 layer (~1957 cal. AD, at 12 and 6 cm) therefore likely reflect recent deposition of the

295 upper ~20 cm of organic matter. The ~1900-yr age difference between the humus at 22

296 cm (1852 cal. BP) versus 12 cm (1957 cal. AD) reflects the reduction in thickness of the

297 humus layer caused by organic matter decay. These results suggest that, under the

298 present-day seasonal climate of the study area, there may be enhanced oxidation of  
299 organic matter during the dry season, leading to incorporation of older, decayed humus  
300 into the top of the mineral layer (Ejsackers and Zehnder, 1990).

#### 301 4.3 C and N analyses

302 C and N results are presented in Supplementary File 1 and in Figure 3. Three main  
303 intervals may be distinguished based on the concentration of TOC and TN. The first  
304 interval, from the base to 50 cm shows slightly elevated TOC (4.9 to 8.9%) and TN  
305 varying from 0.0 to 0.1%. In the interval from 48 cm to 20 cm TOC presents the lowest  
306 concentrations of the core (from 0.8 to 4.0%) and TN varied from 0.0 to 0.1%. The last  
307 interval, from 18 cm upwards, shows increased concentrations of organic matter, with  
308 TOC varying from 12.4 to 56.2%, and TN from 0.2 to 2.7%.

309 These three intervals delimited by TOC and TN concentrations are likely the result of  
310 the process of podzolization. The deficient drainage and the low pH of the studied soil  
311 impeded the fast decomposition of plant litter (van Breemen and Buurman, 1998) causing  
312 the accumulation of peat and high TOC and TN concentrations in the upper interval.  
313 Under this condition soluble organic acids are produced causing the mobilization of the  
314 organic matter and its transport and immobilization into deeper soil horizon (van  
315 Breemen and Buurman, 1998), leading to the leaching of the intermediary interval  
316 (which presents the lowest TOC and TN values) and to the accumulation of organic  
317 matter in the deepest interval.

318 C/N ratios vary between 16.3 and 211.6 (Figure 3). The following four intervals can be  
319 recognized: (i) 56 to 46 cm (>7000 to ~6300 cal. BP), ratios ranging between 81.0 and  
320 160.5 (mean = 118.6). (ii) 46 to 20 cm (5930 to 1715 cal. BP), ratios ranging between  
321 16.3 and 74.5 (mean = 46.5). (iii) 22 to 0 cm (1578 cal. BP to modern), ratios ranging

322 from 47.5 to 211.6 (mean = 123.7). (iv) Modern litter (17.3). For most of the core, the  
323 C/N ratios are indicative of organic matter originating from vascular plants (Table 1).  
324  $\delta^{13}\text{C}$  values vary from -30.3‰ to -25.8‰, in the range of C3 plants (Table 1), which  
325 were likely locally dominant during the entire record. Slightly enriched values occur  
326 from 34-20 cm (from ~4000 to ~1700 cal BP), which may reflect compositional  
327 changes to the local plant community. Alternatively, however, fluctuations in  $\delta^{13}\text{C}$   
328 along the NF core may instead reflect the decomposition and translocation of soil  
329 organic matter through the profile. Enrichment of  $\delta^{13}\text{C}$  with depth (~2.5‰ from 0 to 26  
330 cm) may be related to isotopic fractionation during decomposition (Macko and Estep,  
331 1984; Melillo et al., 1989), while  $\delta^{13}\text{C}$  depletion between 28 and 48 cm may be related  
332 to illuvial and humified material (Kramer et al., 2003).

333  $\delta^{15}\text{N}$  varied from -1.2‰ to +3.3‰ (Figure 3), showing a tendency to more enriched  
334 values from the base to 26 cm (>7000 to ~2600 cal. BP), and relatively stable values  
335 through the organic layer. Considering the influence of decomposition and translocation  
336 processes upon the characteristics of the soil organic matter, it is very likely that  
337 changes in  $\delta^{15}\text{N}$  reflect these processes as well. Depleted  $\delta^{15}\text{N}$  in deeper NF samples  
338 may result from organic matter with low N content and low aliphaticity (Kramer et al.,  
339 2003). For instance, Mafra et al. (2007) found that humic acids extracted from Bh  
340 horizons of Spodosols in northern Amazonia have low N content and low aliphaticity,  
341 signifying humified organic matter translocated down-profile.

#### 342 4.4 Siliceous sponge spicules

343 The presence of freshwater sponge spicules along the entire NF record attests to the  
344 presence of a wetland since ~7000 cal. BP. Figure 4 presents the results of the  
345 qualitative analysis of sponge spicules in NF core as well pictures of diagnostic  
346 spicules. Samples at 50, 40 and 30 cm (7000 – 3300 cal BP) show the presence of



347 megascleres and gemmoscleres of *Racekiela sheilae* . Based on a survey of modern  
348 coastal environments in southern Brazil, Volkmer-Ribeiro and Machado (2007)  
349 concluded that *R. sheilae* colonizes swampy fields or shallow seasonal ponds, close to  
350 dunes or palaeodunes, forming slender crusts on stems of macrophytes and on sand or  
351 gravel conglomerates. Samples at 20, 10 and 4 cm contain megascleres and  
352 gemmoscleres of *R. sheilae* and gemmoscleres of *Anheteromeyenia vitrea* , the latter  
353 identified by Buso Junior et al. (2012) based on live specimens collected at the NF site.  
354 Consequently, the presence of gemmoscleres of *A. vitrea* from 20 cm (~1500 cal. BP)  
355 upwards indicates the onset of environmental conditions similar to those of today,  
356 which are marked by very short periods of flooding.

#### 357 4.5 Palynology

358 Mineral and organic horizons in the NF core contain well-preserved pollen; only one  
359 sample at 54 cm depth was devoid of pollen and spores. Eighty-nine pollen and spores  
360 types were identified and classified as aquatic herbs, trees/shrubs, terrestrial herbs and  
361 terrestrial spores. Total pollen and spore concentrations varied from 3400 to 98,400  
362 grains cm<sup>-3</sup> (Figure 5a), with concentrations increasing above 36 cm depth.

363 Indeterminate and reworked pollen grains varied from 5% to 20%, with higher  
364 frequencies found in the mineral substrate (50 to 20 cm). The cluster analysis allowed  
365 the identification of two pollen assemblage zones. Figure 5a presents the percentage  
366 diagram for selected pollen and spores found in the NF core and the total concentration  
367 in each sample, and Supplementary File 2 presents pollen and spore counts in each  
368 sample.

#### 369 *Pollen Zone NF-I (7043 – 2037 cal. BP; 50 – 23 cm):*

370 This interval is dominated by pollen grains from terrestrial herbs (42-61%; 2800-35,270  
371 grains cm<sup>-3</sup>) followed by trees/shrubs (23-42%; 1279-13,337 grains cm<sup>-3</sup>), aquatic herbs

372 (7-27%; 209-7458 grains cm<sup>-3</sup>) and terrestrial spores (5-14%; 209-3919 grains cm<sup>-3</sup>)  
373 (Figure 5a). Indeterminate and reworked pollen grain frequencies varied from 14% to  
374 20% (437-9481 grains cm<sup>-3</sup>). The most frequent terrestrial herbs are Poaceae (32-54%;  
375 1108-31,161 grains cm<sup>-3</sup>) and Asteraceae (5-6%; 139-2971 grains cm<sup>-3</sup>). The most  
376 frequent trees/shrubs are Myrtaceae (7-17%; 456-4881 grains cm<sup>-3</sup>),  
377 Melastomataceae/Combretaceae (5-10%; 203-3097 grains cm<sup>-3</sup>), *Rheedia* (= *Garcinia*)  
378 *brasiliensis* (6%; 177 grains cm<sup>-3</sup>), Anacardiaceae (2-7%; 209-1705 grains cm<sup>-3</sup>) and  
379 *Alchornea/Aparisthium* (2-4%; 44-2023 grains cm<sup>-3</sup>). Aquatic herbs are represented  
380 mainly by spores of *Salvinia* (7-25%; 209-7016 grains cm<sup>-3</sup>) (Figure 5b).  
381 Based on the presence of a temporary freshwater pond inferred from the *R. sheilae*  
382 spicules, and based on the depleted  $\delta^{13}\text{C}$  values, the Poaceae pollen grains represent C3  
383 terrestrial and semiaquatic species that inhabited the freshwater pond, or swampy field,  
384 and its margins. Some of the tree and shrub taxa (Myrtaceae, Melastomataceae,  
385 *Alchornea*, and Anacardiaceae) would be expected to have colonized the margins and  
386 more elevated areas around this pond. Despite the low frequencies, pollen types such as  
387 *Caryocar*, *Chrysophyllum*, *Eriotheca*, *Pachira*, *Pseudobombax*, *Sapium*, Sapotaceae,  
388 *Senefeldera* and *Parkia* indicate that the *tabuleiros* forest vegetation occurred close to  
389 the study site.  
390 The availability of the pollen reference collection from plants of the study region  
391 allowed the identification of pollen grains of *Rheedia brasiliensis* at the species level  
392 (Figure 5c). *R. brasiliensis* is a generalist species occurring in mesic *mussununga*  
393 forests of the VNR (Simonelli et al., 2008; Siqueira et al., 2014). Elsewhere in  
394 Southeastern Brazil, this species occurs mainly on sandy soils of dry and seasonally  
395 flooded *restingas* (Araújo and Oliveira, 1988; Silva and Oliveira, 1989; Talora and  
396 Morellato, 2000; Duarte et al., 2005). The high frequency (6%) of *Rheedia brasiliensis*,

397 and its exclusive occurrence at the onset of this pollen zone (Figure 5b), may indicate  
398 that a less humid environment occurred at the NF site prior to pollen zone NF-I,  
399 probably a mesic *mussununga*. The absence of *Rheedia brasiliensis* in the subsequent  
400 samples may be the result of the local displacement of this species due to the  
401 establishment of the wetland around 7000 cal. BP.

402 The change of NF site from a mesic *mussununga* to a wetland at ~7000 cal BP is in  
403 accordance with previous pollen,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  based studies, which indicate the onset  
404 of more humid climates at Southern, Central and Southeastern Brazil during the middle  
405 Holocene (Ledru, 1993; Behling, 1997a, 1997b, 2003; Salgado-Labouriau et al., 1998;  
406 Behling and Negrelle, 2001; Garcia et al., 2004; Pessenda et al., 2004, 2009; Cruz et al.,  
407 2005; Veríssimo et al., 2012). Buso Junior et al. (2013a) also inferred an interval of  
408 more humid climatic conditions in the study area between 7000 and 4000 cal. BP.

409 *Pollen Zone NF-II (2037cal. BP – modern; 23cm – litter):*

410 This zone is dominated by trees/shrubs (37-77%; 5963-30,327 grains  $\text{cm}^{-3}$ ), followed by  
411 aquatic herbs (5-76%; 1977-41,329 grains  $\text{cm}^{-3}$ ), terrestrial herbs (14-58%; 5008-21,331  
412 grains  $\text{cm}^{-3}$ ) and terrestrial spores (5-16%; 1129-5931 grains  $\text{cm}^{-3}$ ). Indeterminate and  
413 destroyed pollen grains comprise 5-16% (1832-5352 grains  $\text{cm}^{-3}$ ) (Figure 5a). The most  
414 frequent trees/shrubs are *Alchornea/Aparisthium* (7-43%; 1129-15,684 grains  $\text{cm}^{-3}$ ),  
415 *Myrsine* (3-20%; 434-5566 grains  $\text{cm}^{-3}$ ), Anacardiaceae (1-14%; 289-5140 grains  $\text{cm}^{-3}$ ),  
416 Melastomataceae/Combretaceae (3-6%; 782-2230 grains  $\text{cm}^{-3}$ ), Myrtaceae (2-6%; 589-  
417 2379 grains  $\text{cm}^{-3}$ ), Urticaceae/Moraceae (2-5%; 514-1933 grains  $\text{cm}^{-3}$ ), Arecaceae, (0-  
418 11%; 132-5798 grains  $\text{cm}^{-3}$ ) and *Cecropia* (1-4%; 174-1570 grains  $\text{cm}^{-3}$ ). Aquatic herbs  
419 are represented mainly by *Potamogetom* (0-66%; 0-35,828 grains  $\text{cm}^{-3}$ ), *Salvina* (5-  
420 27%; 1713-8179 grains  $\text{cm}^{-3}$ ), *Typha* (1-7%; 262-1129 grains  $\text{cm}^{-3}$ ) and *Echinodorus* (0-  
421 2%; 0-261 grains  $\text{cm}^{-3}$ ). Among the terrestrial herbs, the most frequent are Cyperaceae

422 (8-54%; 1679-19,761 grains cm<sup>-3</sup>), Poaceae (1-27%; 393-4168 grains cm<sup>-3</sup>) and  
423 Asteraceae (3-6%; 868-1933 grains cm<sup>-3</sup>) (Figure 5b).

424 Among the most important trees/shrubs in the NF-II pollen zone are  
425 *Alchornea/Aparisthium* and *Myrsine*, which are pioneer trees that may be associated  
426 with gallery forests and seasonally flooded lowlands (Marchant et al., 2002). *Myrsine*  
427 *rubra* is a frequent species in the modern environment of the NF site, colonizing its  
428 margins in particular. The depleted  $\delta^{13}\text{C}$  values of the organic matter (Figure 3) indicate  
429 that Cyperaceae and Poaceae pollen grains represent C3 species. In contrast with the  
430 previous pollen zone, NF-II has higher percentages of trees/shrubs and aquatic herbs, as  
431 well as higher numbers of pollen types from trees/shrubs (from 37 types in NF-I to 48 in  
432 NF-II) and terrestrial herbs (from 9 to 13, respectively). Furthermore, unlike NF-I,  
433 where aquatic herbs are dominated by *Salvinia* spores, NF-II has high percentages of  
434 *Potamogeton*, *Salvinia*, *Typha* and *Echinodorus*. These features of the NF-II pollen  
435 zone suggest a change toward a wetland characterized by more closed and diverse  
436 vegetation, indicating the onset of the modern environment at the study site.

437 Some studies of modern plant communities show that the heterogeneity of hydrologic  
438 conditions favours floristic diversity in wetlands, sand dune slacks and *restingas*  
439 (Castellani et al., 1995; Vivian-Smith, 1997; Magnago et al., 2013). These studies found  
440 that permanent flooding is a stress factor for some plant species, reducing their chances  
441 of colonization and establishment in poorly drained areas, favouring the smaller group  
442 of flood-tolerant species. Consequently, the change to a more diverse and closed  
443 vegetation type during the NF-II pollen zone may be due to less frequent and less  
444 intense flooding events at the NF site from ~2000 cal. BP.

445 There may be several reasons for these flood-regime changes at the NF site ~2000 cal.  
446 BP which are not mutually incompatible. One possible cause is increasing seasonality

447 during the late Holocene, as proposed by Buso Junior et al. (2013a) for the study area.  
448 This seasonality would cause the NF site to be flooded during the rainy season and dry  
449 out during the dry season. Another possible explanation is changes in the local relief,  
450 with the reduction of habitable area due to the constant deposition of sand. As described  
451 above (Subsection 4.1), sand grains are found in the organic interval of the NF core,  
452 probably transported from the surrounding *mussununga* forest by water runoff. The  
453 decay process would lead to the destruction of the organic matter, leaving only sand  
454 grains and more resistant organic structures. The vertical increment of the mineral  
455 interval originating from this process would result in a shallower and more ephemeral  
456 water column. Lastly, the relative sea-level fall during the late Holocene (Buso Junior et  
457 al., 2013b) may have lowered the regional base level and thus the local groundwater  
458 level, leading to less frequent flooding of the NF site.

459 Increased frequencies of Urticaceae/Moraceae pollen in NF-II indicate closer proximity  
460 of the *tabuleiros* forest vegetation to the core site. That *tabuleiros* forest was likely  
461 close to the study site is also suggested by the presence of some tree/shrub taxa  
462 characteristic of this vegetation type (e.g. Chrysobalanaceae, *Chrysophyllum*, *Eriotheca*,  
463 *Ficus*, *Glycydendron*, *Rinorea*, *Sapium*, *Senefeldera*, *Simarouba*, *Sloanea*, *Swartzia* and  
464 *Viola*).

#### 465 4.6 Palaeoclimate inferences

466 The presence of pollen grains of *Rheedia brasiliensis* at the beginning of pollen zone  
467 NF-I suggests a less humid environment at the NF site before ~7000 cal. BP. The  
468 subsequent absence of this species, along with the appearance of pollen and spores of  
469 aquatic and semi-aquatic plants and freshwater sponge spicules, suggests the initial  
470 establishment of a wetland around 7000 cal. BP.

471 The transition to a wetland ~7000 cal. BP may be due to the onset of wetter climatic  
472 conditions in Central, Southern and Southeastern Brazil during the middle Holocene,  
473 according with the studies summarized in subsection 1.2. This wetter interval, probably  
474 caused by intensification of the SASM (Cruz et al., 2005, 2006; Prado et al., 2013),  
475 could have raised the groundwater level at the NF site, causing frequent flooding.  
476 However, an alternative, or contributory, cause may be the mid-Holocene rise in  
477 eustatic sea-level, especially because the beginning of pollen zone NF-I (7043 cal. BP)  
478 is coincident with the mid-Holocene sea-level high-stand (Murray-Wallace, 2007; Buso  
479 Junior et al., 2013b), which would have elevated the base level and raised the local  
480 groundwater level.

481 The onset of pollen zone NF-II at ~2000 cal. BP, with more diverse and structurally  
482 complex vegetation, may be due to a decrease in intensity and frequency of flooding, in  
483 turn due to a change toward a more seasonal climate (Buso Junior et al. 2013a). Local,  
484 non-climatic, factors may also have played a role (e.g. local relief changes due to the  
485 deposition of sand, and regional base-level lowering due to the late-Holocene relative  
486 sea-level fall).

#### 487 4.7 The use of tropical sandy soils for pollen studies

488 Important concerns over the feasibility of pollen analysis in soil are the potential for  
489 downwashing of pollen through the profile, bioturbation by soil fauna (Davidson et al.,  
490 1999), and pollen degradation by oxidation (Larocque and Campbell, 1998).

491 However, the distinct assemblages of well preserved pollen and spores in the sandy soil  
492 at NF site demonstrate clear palynological stratigraphy, both in organic and in mineral  
493 horizons, demonstrating that any down-core pollen translocation, bioturbation, or pollen  
494 oxidation must have been relatively insignificant. Good pollen preservation can be  
495 attributed to the low pH and deficient drainage, which reduce bioturbation and

496 microbial activity and hence pollen degradation (Larocque and Campbell, 1998; van  
497 Breemen and Buurman, 1998).

498 We have tested some Spodosol profiles in our study area regarding pollen and spore  
499 preservation and found that profiles from sites which were not water-saturated during  
500 the dry season were devoid of pollen and spores. This suggests that the redoximorphic  
501 conditions, provided by water saturation during most of the year, explains the good  
502 pollen preservation in the NF profile as well.

503 The preservation of the pollen stratigraphy in the NF core shows that pollen grains  
504 cannot have been transported along with the organic matter. We suggest that the  
505 mechanism responsible for the incorporation of pollen, spores and sponge spicules in  
506 the NF core was the gradual deposition of the organic matter and sand on the soil  
507 surface and the subsequent decomposition of this organic matter, leaving behind the  
508 resistant pollen.

509 Pollen records from soils usually represent the local vegetation (Larocque and  
510 Campbell, 1998). Consequently, interpretation of pollen data from soil samples must  
511 take into account local features that may influence vegetation dynamics. This is the case  
512 for the present study, where local conditions have an important role in the maintenance  
513 of water saturated soil, even during the dry season. Another important factor influencing  
514 the vegetation at the NF site is the change in local relief, which influences the depth of  
515 the water column and the persistence of surface water. Analysis of pollen from several  
516 soil profiles in a given region has the potential for reconstructing vegetation histories at  
517 much higher spatial resolution than is possible from large lakes with regionally-  
518 smoothed pollen catchments. Furthermore, pollen records from tropical waterlogged  
519 sandy soils may be of great importance for palaeoecological studies in regions where

520 peat bogs and natural lakes are rare or absent; e.g. southern Bahia, northern Espírito  
521 Santo, and the white-sand vegetation of northern Amazonia.

## 522 **5. Conclusions**

### 523 5.1. Distribution and characteristics of organic matter

524 C and N data from the NF core indicate that organic matter has originated  
525 predominantly from vascular C3 plants since 7000 cal. BP. However, decomposition  
526 and translocation processes have influenced the characteristics and the distribution of  
527 the organic matter in the soil profile, with the accumulation of organic matter in the  
528 upper and lower horizons and depletion of organic matter in the intermediary horizon. .  
529 Small enrichments of  $\delta^{13}\text{C}$  likely reflect isotopic fractionation during decomposition.  
530 Down-core depletion of  $\delta^{15}\text{N}$  may reflect translocation of humified organic matter to  
531 lower soil horizons.

### 532 5.2. Biological proxies in the waterlogged sandy soil

533 The waterlogged sandy soil at NF site has well preserved biological proxies (pollen,  
534 spores and sponge spicules), both in organic and mineral intervals. Clear stratigraphic  
535 changes in these proxies demonstrate that down-core translocation and bioturbation  
536 (e.g. by soil fauna) must have been minimal, while the low pH and redoximorphic soil  
537 conditions prevented the degradation of pollen and spores.

538 These biological proxies indicate the transition from a mesic *mussununga* to a wetland  
539 ~7000 cal. BP. Between ~7000 and ~2000 cal. BP this wetland was a swamp or  
540 freshwater pond, colonized mainly by aquatic and semiaquatic C3 plants and the  
541 freshwater sponge *R. sheilae*. At ~2000 cal. BP the wetland began to be colonized by a  
542 more diverse flora, composed of aquatic and semiaquatic plants, trees and shrubs.  
543 The transition from the mesic *mussununga* to a wetland ~7000 cal. BP suggests a  
544 change to wetter climate at this time, which is in accordance with previous studies from



545 central, southern and southeastern Brazil. The subsequent colonization of the wetland  
546 by a more diverse vegetation at ~2000 cal. BP signifies the onset of environmental  
547 conditions similar to those of today, with more frequent and intense flood events  
548 restricted to the wet season. A change to a more seasonal climate, changes in local  
549 relief, and a fall in relative sea-level are the likely drivers of these late Holocene  
550 environmental changes at the study site.

551 Our results suggest that useful palaeoecological information can be retrieved via  
552 analysis of pollen and spores from waterlogged sandy soils in tropical environments.  
553 Analysis of several depressions from a given region has the potential to provide  
554 palaeoecological information at much finer spatial resolution than is possible from lakes  
555 in these areas, most of which yield environmental records at much coarser spatial  
556 resolution due to their much larger pollen catchments associated with their larger areas.

557

### 558 **Acknowledgements**

559 The authors would like to thank Vale Nature Reserve (Linhares, Brazil) for the field  
560 support and Cassio Fernando França de Negri for the X-ray image. This work was  
561 supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (São Paulo  
562 Foundation for Research Support – FAPESP) [grant numbers 2007/06222-4,  
563 2007/03615-5, 2010/18091-4 and 2011/00995-7], CNPq [grant number 245858/2012-1  
564 SWE/CSF] and CAPES/PROEX.

565

### 566 **References**

567 Araújo, D.S.D., Oliveira, R.R., 1988. Reserva Biológica Estadual da Praia do Sul (Ilha  
568 Grande, estado do Rio de Janeiro): lista preliminar da flora. *Acta Botanica Brasilica* 1  
569 (2), 83-94.

570 Bałaga, K., Chodorowski, J., 2006. Pollen analysis from fossil podzol soils within a  
571 dune at Kaczórki (Middle Roztocze, Poland). *Acta Palaeobotanica* 46 (2), 245-254.

572 Behling, H., 1997a. Late Quaternary vegetation, climate and fire history from the  
573 tropical mountain region of Morro de Itapeva, SE Brazil. *Palaeogeography,*  
574 *Palaeoclimatology, Palaeoecology* 129, 407-422.

575 Behling, H., 1997b. Late Quaternary vegetation, climate and fire history of the  
576 Araucaria forest and campos region from Serra Campos Gerais, Paraná State (south  
577 Brazil). *Review of Palaeobotany and Palynology* 97, 109-121.

578 Behling, H., 2003. Late Glacial and Holocene vegetation, climate and fire history  
579 inferred from Lagoa Nova in the southeastern Brazilian lowland. *Vegetation History*  
580 *and Archaeobotany* 12, 263-270.

581 Behling, H., Negrelle, R., 2001. Tropical rain forest and climate dynamics of the  
582 Atlantic Lowland, Southern Brazil, during the late Quaternary. *Quaternary Research* 56,  
583 383-389.

584 Boulet, R., Pessenda, L.C.R., Telles, E.C.C., Melfi, A.J., 1995. Une évaluation de la  
585 vitesse de l'accumulation superficielle de matière par la faune du sol à partir de la  
586 datation des charbons et de l'humine du sol. Example des latosols des versants du lac  
587 Campestre, Salitre, Minas Gerais, Brésil. *Compte Rendus de l'Academie des Sciences.*  
588 *Serie 2* 320, 287-294.

589 Boutton, T.W., 1991. Stable carbon isotope ratios of natural materials. II. Atmospheric,  
590 terrestrial, marine and freshwater environments, in: Coleman, D.C., Fry, B. (Eds.),  
591 *Carbon isotope techniques.* Academic Press, New York, pp. 155-171.

592 Buso Junior, A.A., Volkmer-Ribeiro, C., Pessenda, L.C.R., Machado, V.S., 2012.  
593 *Anheteromeyenia vitrea* (Porifera: Demospongiae) new species of continental sponge in  
594 Brazil. *Neotropical Biology and Conservation* 7 (3), 148-157.

595 Buso Junior, A.A., Pessenda, L.C.R., De Oliveira, P.E., Giannini, P.C.F., Cohen,  
596 M.C.L., Volkmer-Ribeiro, C., Oliveira, S.M.B., Rossetti, D.F., Lorente, F.L., Borotti  
597 Filho, M.A., Schiavo, J.A., Bendassolli, J.A., França, M.C., Guimarães, J.T.F., Siqueira,  
598 G.S., 2013a. Late Pleistocene and Holocene vegetation, climate dynamics, and  
599 Amazonian taxa in the Atlantic Forest, Linhares, SE Brazil. *Radiocarbon* 55 (2-3),  
600 1747-1762.

601 Buso Junior, A.A., Pessenda, L.C.R., De Oliveira, P.E., Giannini, P.C.F., Cohen,  
602 M.C.L., Volkmer-Ribeiro, C., Oliveira, S.M.B., Favaro, D.I.T., Rossetti, D.F., Lorente,  
603 F.L., Borotti Filho, M.A., Schiavo, J.A., Bendassolli, J.A., França, M.C., Guimarães,  
604 J.T.F., Siqueira, G.S., 2013b. From an estuary to a freshwater lake: a paleo-estuary  
605 evolution in the context of Holocene sea-level fluctuations, SE Brazil. *Radiocarbon* 55  
606 (2-3), 1735-1746.

607 Calegari, M.R., Madella, M., Brustolin, L.T., Pessenda, L.C.R., Buso Junior, A.A.,  
608 Francisquini, M.I., Bendassolli, J.A., Vidal-Torrado, P., 2017. Potential of soil  
609 phytoliths, organic matter and carbon isotopes for small-scale differentiation of tropical  
610 rainforest vegetation: A pilot study from the campos nativos of the Atlantic Forest in  
611 Espírito Santo State (Brazil). *Quaternary International* 437 (Part B), 156-164.

612 Castellani, T.T., Folchini, R., Scherer, K.Z., 1995. Variação temporal da vegetação em  
613 um trecho de baixada úmida entre dunas, Praia da Joaquina, Florianópolis, SC. *Insula*  
614 24, 37-72.

615 Colinvaux, P., De Oliveira, P.E., Patiño, J.E.M., 1999. Amazon pollen manual and atlas.  
616 Manual e atlas palinológico da Amazônia. Amsterdam: Harwood Academic Publishers.

617 Cruz Jr, F.W., Burns, S.J., Karmann, I., Sharp, W.D., Vuille, M., Cardoso, A.O.,  
618 Ferrari, J.A., Dias, P.L.S., Viana Jr, O., 2005. Insolation-driven changes in atmospheric  
619 circulation over the past 116,000 years in subtropical Brazil. *Nature* 434 (7029), 63-66.

620 Cruz Jr, F.W., Burns, S.J., Karmann, I., Sharp, W.D., Vuille, M., Ferrari, J.A., 2006. A  
621 stalagmite record of changes in atmospheric circulation and soil processes in the  
622 Brazilian subtropics during the Late Pleistocene. *Quaternary Science Reviews* 25, 2749-  
623 2761.

624 Davidson, D.A., Carter, S., Boag, B., Long, D., Tipping, R., Tyler, A., 1999. Analysis  
625 of pollen in soils: processes of incorporation and redistribution of pollen in five soil  
626 profile types. *Soil Biology and Biochemistry* 31, 643-653.

627 Dimbleby, G.W., 1952. The historical status of Moorland in North-East Yorkshire. *The*  
628 *New Phytologist* 51 (3), 349-354.

629 Dominguez, J.M.L., 2009. The coastal zone of Brazil, in: Dillenburg, S.R., Hesp, P.A.  
630 (Eds.), *Geology and geomorphology of Holocene coastal barriers of Brazil*. Springer-  
631 Verlag, Berlin, pp. 17-46.

632 Duarte, H.M., Geßler, A., Scarano, F.R., Franco, A.C., Mattos, E.A., Nahm, M.,  
633 Rennenberg, H., Rodrigues, P.J.F.P., Zaluar, H.L.T., Lüttge, U., 2005. Ecophysiology  
634 of six selected shrub species in different plant communities at the periphery of the  
635 Atlantic Forest of SE-Brazil. *Flora* 200, 456-476.

636 Dubroeuq, D., Volkoff, B., 1998. From Oxisols to Spodosols and Histosols: evolution  
637 of the soil mantles in the Rio Negro basin (Amazonia). *Catena* 32, 245-280.

638 Ejsackers, H., Zehnder, A.J.B., 1990. Litter decomposition: a Russian matriochka doll.  
639 *Biogeochemistry* 11, 153-174.

640 Ferreira, V.B.R., Nascimento, M.T., De Menezes, L.F.T., 2014. Floristic and  
641 phytogeography pattern of native field in southeastern Brazil. *Acta Botanica Brasilica*  
642 28 (3), 465-475.

643 Garcia, M.J., De Oliveira, P.E., Siqueira, E. Fernandes, R.S., 2004. A Holocene  
644 vegetational and climatic record from the Atlantic rainforest belt of coastal State of São  
645 Paulo, SE Brazil. *Review of Palaeobotany and Palynology* 131, 181-199.

646 Garreaud, R.D., Vuille, M., Compagnucci, R., Marengo, J., 2009. Present-day South  
647 American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology* 281, 180-195.

648 Gouveia, S.E.M., Pessenda, L.C.R., Aravena, R., Boulet, R., Scheel-Ybert, R.,  
649 Bendassolli, J.A., Ribeiro, A.S., Freitas, H.A., 2002. Carbon isotopes in charcoal and  
650 soils in studies of paleovegetation and climate changes during the late Pleistocene and  
651 the Holocene in the southeast and centerwest regions of Brazil. *Global and Planetary  
652 Change* 33, 95-106.

653 Grimm, E.C., 1987. CONISS: a Fortran 77 program for stratigraphically constrained  
654 cluster analysis by the method of incremental sum of squares. *Computers and  
655 Geosciences* 13 (1), 13-35.

656 Grimm, E.C., 1992. Tilia and Tilia-graph: pollen spreadsheet and graphics program.  
657 Program and Abstracts, 8<sup>th</sup> International Palynological Congress. Aix-en-Provence, 56.

658 Guillet, B., 1970. Étude palynologique des podzols. I. La podzolisation sur alluvions  
659 anciennes en Lorraine. *Pollen et Spores* 12 (1), 45-69.

660 Guillet, B., 1971a. Étude palynologique des podzols. II. La podzolisation sur les  
661 versants secs greseux de Basses-Vosges. *Pollen et Spores* 13 (2), 233-254.

662 Guillet, B., 1971b. Étude palynologique des podzols. III. La podzolisation sur granite  
663 dans les Vosges hercyniennes de l'étage Montagnard. Comparaison avec la  
664 podzolisation dan les Basses Vosges gréseuses et sur le Plateau Lorrain. *Pollen et  
665 Spores* 13 (3), 421-446.

666 Hogg, A.G., Hua, Q., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., Heaton,  
667 T.J., Palmer, J.G., Reimer, P.J., Reimer, R.W., Turney, C.S.M., Zimmerman, S.R.H.,

668 2013. SHCal13 Southern Hemisphere calibration, 0-50,000 years cal BP. Radiocarbon  
669 55 (4), 1889-1903.

670 Jacobson Jr., G.L., Bradshaw, R.H.W., 1981. The selection of sites for  
671 paleovegetational studies. Quaternary Research 16, 80-96.

672 Kramer, M.G., Sollins, P., Sletten, R.S., Swart, P.K., 2003. N isotope fractionation and  
673 measures of organic matter alteration during decomposition. Ecology 84(8), 2021-2025.

674 Larocque, I., Campbell, I.D., 1998. La stratigraphie pollinique en humus de podzols.  
675 Sustainable Forest Management Network. Working Paper, 16, 1-22.

676 Ledru, M.P., 1993. Late Quaternary environmental and climatic changes in Central  
677 Brazil. Quaternary Research 39, 90-98.

678 Lorente, F.L., Buso Junior, A.A., De Oliveira, P.E., Pessenda, L.C.R., 2017. Atlas  
679 palinológico: Laboratório <sup>14</sup>C – CENA/USP = Palynological atlas: <sup>14</sup>C Laboratory –  
680 CENA/USP. FEALQ, Piracicaba.

681 Macario, K.D., Gomes, P.R.S., Anjos, R.M., Carvalho, C., Linares, R., Alves, E.Q.,  
682 Oliveira, F.M., Castro, M.D., Chanca, I.S., Silveira, M.F.M., Pessenda, L.C.R., Moraes,  
683 L.M.B., Campos, T.B., Cherkinsky, A., 2013. The Brazilian AMS radiocarbon  
684 laboratory (LAC-UFF) and the intercomparison of results with CENA and UGAMS.  
685 Radiocarbon 55(2-3), 325-330.

686 Macko, S.A., Estep, M.L.F., 1984. Microbial alteration of stable nitrogen and carbon  
687 isotopic compositions of organic matter. Organic Geochemistry 6, 787-790.

688 Mafra, A.L., Senesi, N., Brunetti, G., Miklós, A.A.W., Melfi, A.J., 2007. Humic acids  
689 from hidromorphic soils of the upper Negro river basin, Amazonas: Chemical and  
690 spectroscopic characterization. Geoderma 138, 170-176.

691 Magnago, L.F.S., Martins, S.V., Schaefer, C.E.G.R., Neri, A.V., 2013. Structure and  
692 diversity of *restingas* along a flood gradient in southeastern Brazil. *Acta Botanica*  
693 *Brasilica* 27 (4), 801-809.

694 Marchant, R., Almeida, L., Behling, H., Berrio, J.C., Bush, M., Cleef, A.,  
695 Duivenvoorden, J., Kappelle, M., De Oliveira, P.E., Oliveira-Filho, A.T., Lozano-  
696 García, S., Hooghiemstra, H., Ledru, M.P., Ludlow-Wiechers, B., Markgraf, V.,  
697 Mancini, V., Paez, M., Prieto, A., Rangel, O., Salgado-Labouriau, M.L., 2002.  
698 Distribution and ecology of parent taxa of pollen lodged within the Latin America  
699 Pollen Database. *Review of Palaeobotany and Palynology* 121, 1-75.

700 Matsuura, Y., Wada, E., 1994. Carbon and nitrogen stable isotope ratios in marine  
701 organic matters of the coastal ecosystem in Ubatuba, southern Brazil. *Ciência e Cultura*  
702 46, 141-146.

703 Meira-Neto, J.A.A., Souza, A.L., Lana, J.M., Valente, G.E., 2005. Composição  
704 florística, espectro biológico e fitofisionomia de vegetação de muçununga nos  
705 municípios de Caravelas e Mucuri, Bahia. *Revista Árvore* 29 (1), 139-150.

706 Melillo, J.M., Aber, J.D., Linkins, A.E., Ricca, A., Fry, B., Nadelhoffer, K.J., 1989.  
707 Carbon and nitrogen dynamics along the decay continuum: Plant litter to soil organic  
708 matter. *Plant and Soil* 115, 189-198.

709 Meyers, P.A., 2003. Applications of organic geochemistry to paleolimnological  
710 reconstructions: a summary of examples from the Laurentian Great Lakes. *Organic*  
711 *Geochemistry* 34, 261-289.

712 Moreau, A.M.S.S., Ker, J.C., Costa, L.M., Gomes, F.H., 2006. Caracterização de solos  
713 de duas topossequências em tabuleiros costeiros do sul da Bahia. *Revista Brasileira de*  
714 *Ciência do Solo* 30, 1007-1019.

715 Murray-Wallace, C.V., 2007. Eustatic sea-level changes since the last glaciation, in:  
716 Elias, S.A. (Ed), Encyclopedia of Quaternary science. Elsevier, Amsterdam, pp. 3034-  
717 3043.

718 Oliveira, A.P., Ker, J.C., Silva, I.R., Fontes, M.P.F., Oliveira, A.P., Neves, A.T.G.,  
719 2010. Spodosols pedogenesis under Barreiras Formation and sandbank environments in  
720 the South of Bahia. *Revista Brasileira de Ciência do Solo*, 34, 847-860.

721 Peixoto, A.L., Gentry, A., 1990. Diversidade e composição florística da mata de  
722 tabuleiros na Reserva Florestal de Linhares (Espírito Santo, Brasil). *Revista Brasileira*  
723 *de Botânica* 13 (1), 19-25.

724 Pessenda, L.C.R., Gouveia, S.E.M., Aravena, R., Boulet, R., Valencia, E.P.E., 2004.  
725 Holocene fire and vegetation changes in southeastern Brazil as deduced from fossil  
726 charcoal and soil carbon isotopes. *Quaternary International* 114, 35-43.

727 Pessenda, L.C.R., De Oliveira, P.E., Mofatto, M., Medeiros, V.B., Garcia, R.J.F.,  
728 Aravena, R., Bendassolli, J.A., Leite, A.Z., Saad, A.R., Etchebehere, M.L., 2009. The  
729 evolution of a tropical rainforest/grassland mosaic in southeastern Brazil since 28,000  
730  $^{14}\text{C}$  yr BP based on carbon isotopes and pollen records. *Quaternary Research* 71, 437-  
731 452.

732 Prado, L.F., Wainer, I., Chiessi, C.M., Ledru, M.-P., Turcq, B., 2013. A mid-Holocene  
733 climate reconstruction for eastern South America. *Climate of the Past* 9, 2117-2133.

734 Rau, G.H., Takahashi, T., Des Marais, D.J., 1989. Latitudinal variations in plankton  
735  $\delta^{13}\text{C}$ : implications for  $\text{CO}_2$  and productivity in past oceans. *Nature* 341 (6242), 516-518.

736 Saia, S.E.M.G., Pessenda, L.C.R., Gouveia, S.E.M., Aravena, R., Bendassolli, J.A.,  
737 2008. Last glacial maximum (LGM) vegetation changes in the Atlantic Forest,  
738 southeastern Brazil. *Quaternary International* 184, 195-201.



739 Salgado-Labouriau, M.L, Barberi, M., Ferraz-Vicentini, K.R., Parizzi, M.G., 1998. A  
740 dry climatic event during the late Quaternary of tropical Brazil. Review of  
741 Palaeobotany and Palynology 99, 115-129.

742 Santos, R.D., Barreto, W.O., Silva, E.F., Araújo, W.S., Claessen, M.E.C., Paula, J.L.,  
743 Souza, J.L.R., Pérez, D.V., Souza, J.S., 2004. Levantamento expedito dos solos das  
744 reservas florestais de Linhares e Sooretama no estado do Espírito Santo. EMBRAPA  
745 Solos, 66 p.

746 Santos, G.M., Linares, R., Lisi, C.S., Tomazello Filho, M., 2015. Annual growth rings  
747 in a sample of Paraná pine (*Araucaria angustifolia*): Toward improving the <sup>14</sup>C  
748 calibration curve for the Southern Hemisphere. Quaternary Geochronology 25, 96-103.

749 Saporetti-Junior, A.W., Schaefer, C.E.R., Souza, A.L., Soares, M.P., Araújo, D.S.D.,  
750 Meira-Neto, J.A.A., 2012. Influence of soil physical properties on plants of the  
751 mussununga ecosystem, Brazil. Folia Geobotanica 47, 29-39.

752 Scharpenseel, H.W., Becker-Heidmann, P., 1992. Twenty-five years of radiocarbon  
753 dating soils: paradigm of erring and learning. Radiocarbon 34(3), 541-549.

754 Secretti, M.L., 2013. Caracterização e classificação de solos de campos nativos no  
755 nordeste do Espírito Santo. Ms Thesis, State University of Mato Grosso do Sul, Brazil.

756 Silva, J.G., Oliveira, A.S., 1989. A vegetação de restinga no município de Maricá – RJ  
757 (1). Acta Botanica Brasilica 3 (2), 253-272.

758 Simonelli, M., Souza, A.L., Peixoto, A.L., Silva, A.F., 2008. Floristic composition and  
759 structure of the tree component of a muçununga forest in the Linhares Forest Reserve,  
760 Espírito Santo, Brazil, in: Thomas, W.W., Britton, E.G., The Atlantic coastal forest of  
761 Northeastern Brazil. Memoirs of the New York Botanical Garden 100, pp. 345-364.

762 Siqueira, G.S., Kierulf, M.C.M., Alves-Araújo, A., 2014. Florística das plantas  
763 vasculares da Reserva Natural Vale, Linhares, Espírito Santo, Brasil. *Ciência &*  
764 *Ambiente* 49, 67-129.

765 Stuiver, M., Reimer, P.J., 1993. Extended  $^{14}\text{C}$  database and revised CALIB 3.0  $^{14}\text{C}$   
766 calibration program. *Radiocarbon* 35 (1), 215-230.

767 Talora, D.C., Morellato, P.C., 2000. Fenologia de espécies arbóreas em floresta de  
768 planície litorânea do sudeste do Brasil. *Revista Brasileira de Botânica* 23 (1), 13-26.

769 Tavares, M.C.M., Volkmer-Ribeiro, C., De Rosa-Barbosa, R., 2003. Primeiro registro  
770 de *Corvoheteromeyenia australis* (Bonetto & Ezcurra de Drago) para o Brasil com  
771 chave taxonômica para os poríferos do Parque Estadual Delta do Jacuí, Rio Grande do  
772 Sul, Brasil. *Revista Brasileira de Zoologia* 20 (2), 169-182.

773 Teixeira, P.C., Campos, D.V.B., Saldanha, M.F.C., 2017. pH do solo. In: Teixeira, P.C.,  
774 Donagemma, G.K., Fontana, A., Teixeira, W.G. (Eds.), *Manual de métodos de análise*  
775 *do solo*. EMBRAPA, Brasília, pp. 199-202.

776 Thomas, W.W., 2003. Natural vegetation types in southern Bahia. In: Prado, P.I.,  
777 Landau, E.C., Moura, R.T., Pinto, L.P.S., Fonseca, G.A.B., Alger, K.N. (org.). *Corredor*  
778 *de biodiversidade da Mata Atlântica do sul da Bahia*. IESB, CI, CABS, UFMG,  
779 UNICAMP. CD-ROM.

780 van Breemen, N., Buurman, P., 1998. *Soil formation*. Kluwer Academic Publishers,  
781 Dordrecht, The Netherlands, pp. 245-270.

782 Veríssimo, N., Safford, H.D., Behling, H., 2012. Holocene vegetation and fire history of  
783 the Serra do Caparaó, SE Brazil. *The Holocene* 22(11), 1243-1250.

784 Vivian-Smith, G., 1997. Microtopographic heterogeneity and floristic diversity in  
785 experimental wetland communities. *The Journal of Ecology*, 85 (1), 71-82.

786 Volkmer-Ribeiro, C., Machado, V.S., 2007. Freshwater sponges (Porifera,  
787 Demospongiae) indicators of some coastal habitats in South America: redescrptions  
788 and key to identification. *Iheringia, Sér. Zool.* 97 (2), 157-167.

789 Volkmer-Ribeiro, C., Motta-Marques, D., De Rosa-Barbosa, R., Machado, V.S., 2006.  
790 Sponge spicules in sediments indicate evolution of coastal freshwater bodies. *Journal of*  
791 *Coastal Research* 39, 469-472.

792 Wada, E., Kabaya, Y., Mitamura, O., Saijo, Y., Tundisi, J.G., 1989. Stable isotopic  
793 studies on the Rio Doce Valley lake ecosystem in Brazil. In: Saijo, Y., Tundisi, J.G.  
794 (Eds.), *Limnological studies in Rio Doce Valley lakes, Brazil*. Nagoya University,  
795 Nagoya, pp. 71-76.

796 Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. *J. Geol.*  
797 30, 377-392.

798

Table 1 –  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and C/N of different organic matter sources

Organic matter source	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)	C/N
Vascular C3 plants	-33 to -20	$\approx +1$	$\geq 20$
Vascular C4 plants	-17 to -9	$\approx +1$	$\geq 20$
Freshwater phytoplankton	-37 to -25	$\approx +8$	4 to 10
Marine phytoplankton <sup>(1)</sup>	$\approx -21$	$\approx +8$	4 to 10

<sup>(1)</sup> At southern tropical latitudes;

According to: Rau et al. (1989); Wada et al. (1989); Boutton (1991); Matsuura and Wada (1994); Meyers (2003)

Table 2 – Hydrolysis parameters and results of samples for AMS  $^{14}\text{C}$  analysis

Sample	Depth (cm)	Hydrolysis	Laboratory code	$^{14}\text{C}$ (BP)	Age (cal. BP; 2 $\sigma$ )	Mean (cal. BP)
NF07-05	05-07	2% HCl; 60 °C; 4 h	UGAMS28371	102.436 $\pm$ 0.297 <sup>a</sup>	1957.0-1957.4 <sup>b</sup>	1957 <sup>b</sup>
NF13-11	11-13	2% HCl; 60 °C; 4 h	UGAMS28375	102.913 $\pm$ 0.308 <sup>a</sup>	1957.2-1957.6 <sup>b</sup>	1957 <sup>b</sup>
NF23-21	21-23	1% HCl; 4 h	LACUFF150039	1937 $\pm$ 51	1991-1713	1852
NF49-47	47-49	1% HCl; 60 °C; 1 h	LACUFF150040	5906 $\pm$ 40	6788-6555	6672
NF51-49	49-51	2% HCl; 4 h	UGAMS15861	5320 $\pm$ 30	6181-5941	6061

UGAMS: AMS Laboratory of University of Georgia; LACUFF: AMS Laboratory of Universidade Federal Fluminense.

<sup>a</sup>  $^{14}\text{C}$  activity in pMC.

<sup>b</sup> Calibrated age in cal AD.

Table 3 – pH of selected intervals in NF core

Depth (cm)	pH (H <sub>2</sub> O)	pH (KCl)
00-19	4.8	3.2
19-25	5.7	3.6
29-35	5.4	3.8
39-45	5.3	3.9
51-57	4.5	3.4

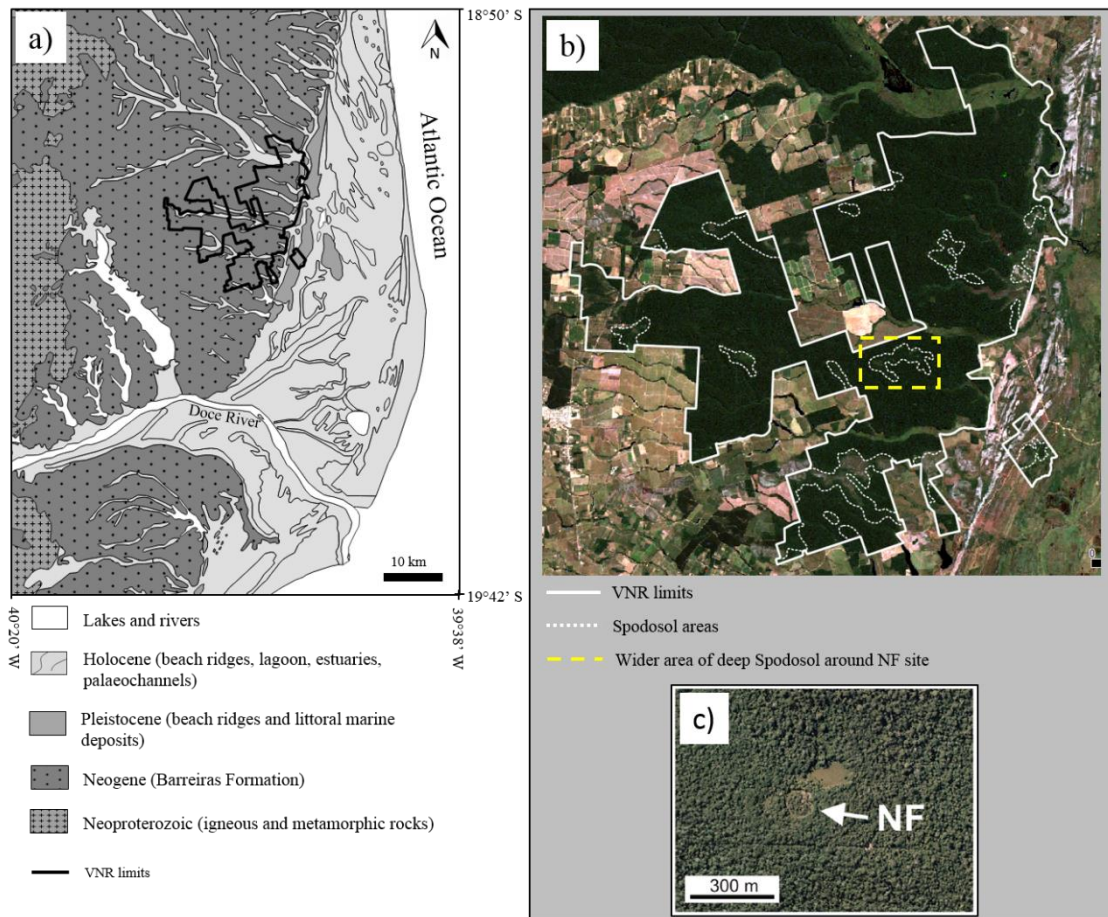


Figure 1 – Study area. a) Geologic map for the Northeastern coast of Espírito Santo State. b); Landsat 7 RGB123 composition and the Spodosol areas delimited by Santos et al. (2004) in the VNR; c) NF site.

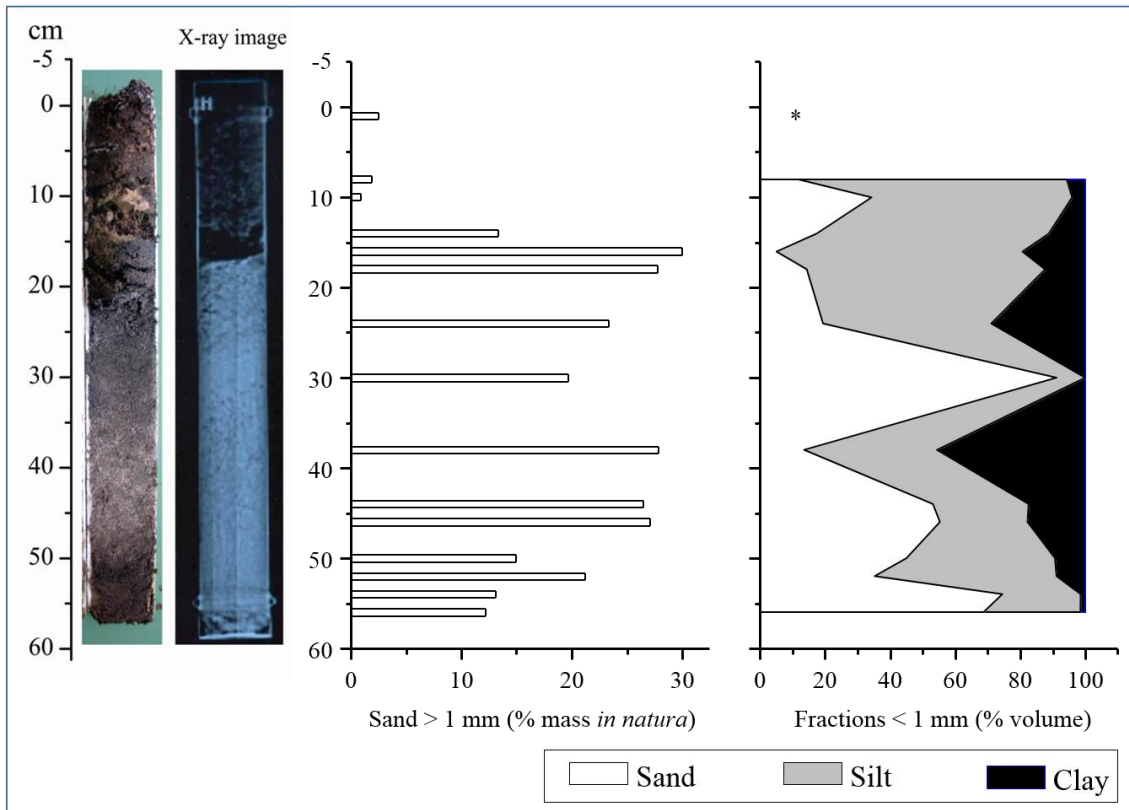


Figure 2 – NF core: photograph, X-ray image and grain size distribution. (\*) sample 03-00 cm was lost during laser diffraction analysis.

804

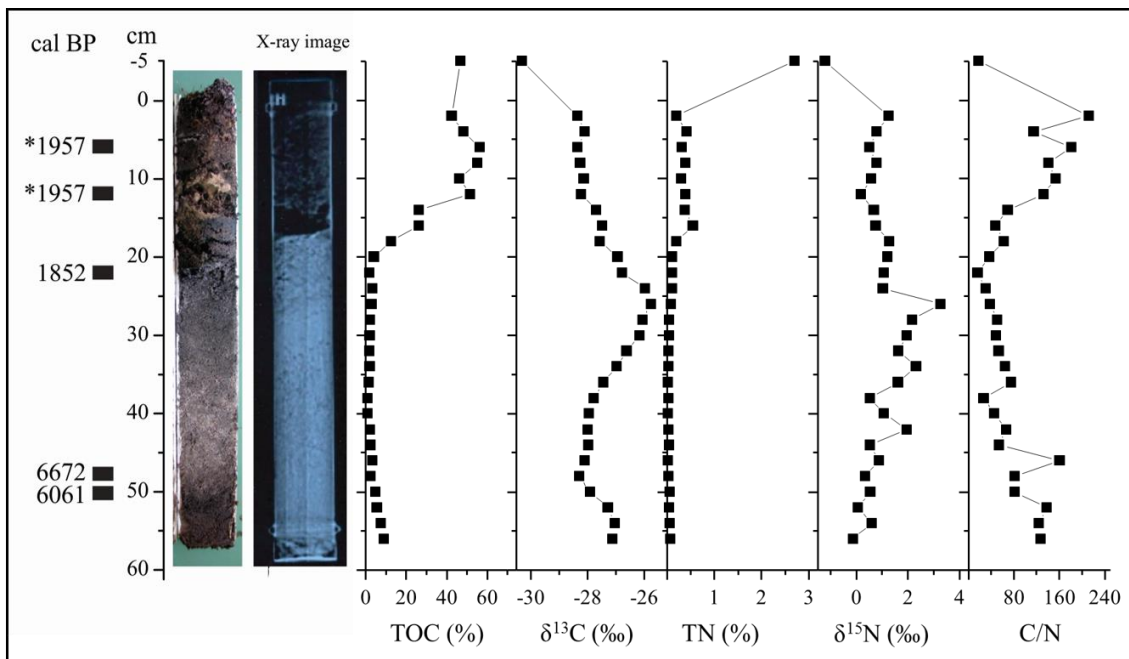


Figure 3 – C and N results from NF core. \*ages in cal AD.

805

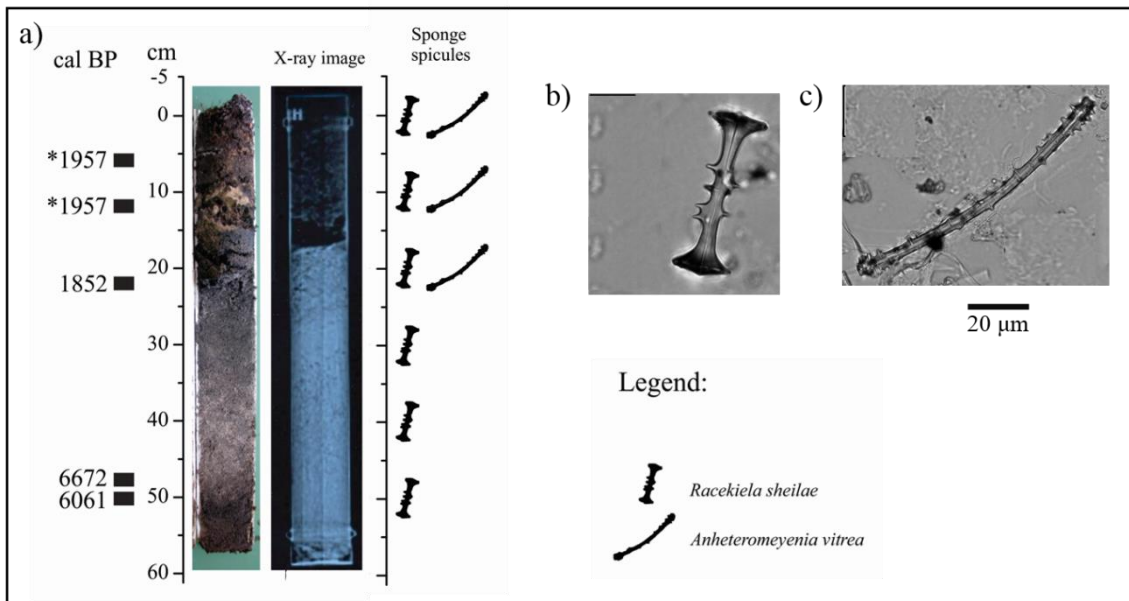


Figure 4 – a) Presence of siliceous sponge spicules. Gemmoscleres of *Racekiela sheilae* (b) and *Anheteromeyenia vitrea* (c). \*age in cal AD.

806

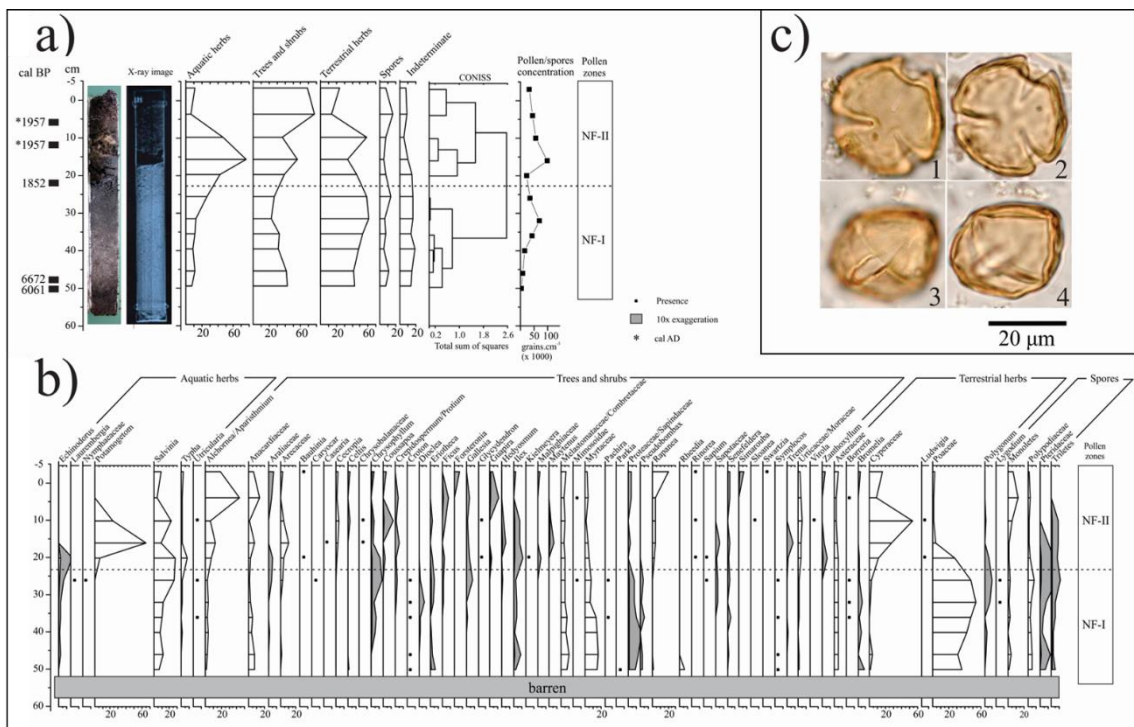


Figure 5 – a) Pollen and spores groups percentages, CONISS results, pollen and spores concentrations and pollen zones. b) Percentage diagram of selected taxa and pollen zones. c) Photographs of *Rheedea brasiliensis* pollen grain (1-2: polar view; 3-4: equatorial view).

807