Late Holocene mangrove dynamics of the Doce River delta, southeastern Brazil: implications for the understanding of mangrove resilience to sea-level changes and channel dynamics

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1 **Late Holocene mangrove dynamics of the Doce River delta, southeastern Brazil:**

2 **Implications for the understanding of mangrove resilience to sea-level changes and**

3 **channel dynamics**

4

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ABSTRACT

This work aims to understand mangrove resilience to changes in a wave-influenced delta in southeastern Brazil during the late Holocene using an integrated analysis of palynology, sedimentology, and geochemistry (δ^{13}C, δ^{15}N, C:N and C:S ratio), and radiocarbon dating on two sediment cores. The data indicated three mangrove succession phases: 1) an estuarine point bar/tidal flat occupied by a mixture of mangrove species (~2660 - ~2050 cal yr BP); 2) a tidal flat dominated by *Laguncularia* mangroves (~2050 - ~900 cal yr BP); and 3) tidal flats with *Laguncularia* mangroves upstream and establishment of *Rhizophora/Avicennia* mangrove at the river mouth (~900 cal yr BP until present). The geochemical results suggest a dominance of C$_3$ terrestrial plants with a mixture of C$_4$ plants and organic matter of marine/estuarine origin throughout the late Holocene. *Laguncularia* and *Rhizophora* trees were established since ~2660 cal yr BP as pioneers, followed thereafter by *Avicennia*. Currently, tidal flats upstream are occupied by mangroves mainly represented by *Laguncularia*. *Rhizophora/Avicennia* mangroves occur at the mouth of the river. The relative sea-level fall during the late Holocene, as well as the channel dynamics, caused the development of tidal flats and mangrove succession inland. The succession of *Rhizophora*, *Laguncularia,* and *Avicennia*, followed by the permanence of only *Laguncularia*, is likely related to the resilience of each mangrove genus to habitat disturbance (e.g., salinity and sediment grain size fractions) caused by sea-level changes and channel dynamics. Our results show that mangroves may be resilient to the effects of Atlantic sea-level fluctuations, but the floristic structure in the past is different from that of today.

Keywords: Pollen; sea-level; stable isotopes; transitional sediments; wave-influenced.

1. Introduction

The global distribution of mangroves has changed throughout geological and human history (Monacci et al., 2009). Studies along the Brazilian littoral zone using multi-proxy data have indicated expansion and contraction of mangrove areas during the Holocene (Amaral et al., 2006; Pessenda et al., 2008; Cohen et al., 2009; Smith et al., 2011; França et al., 2012; Guimarães et al., 2012; França et al., 2013, 2016). This mangrove dynamic is due to the combination of sea-level changes (Angulo et al., 2008), tectonic activities (Rossetti et al., 2012), and variations in fluvial discharge related to climate changes (Bush and Colinvaux, 1990; Bush et al., 2007). Mangroves are affected by complex interactions between tidal flood frequency, sediment and nutrient supply, and porewater salinity of intertidal flats (Hutchings and Saenger, 1987; Wolanski et al., 1990; Masselink and Gehrels, 2015). Mangrove species differ in their responses to local variations in environmental conditions (Tomlinson, 1986).

Regarding natural influences on deltaic systems, sea-level fluctuations have affected coastal ecosystems, such as mangroves, along the Brazilian littoral (Lara and Cohen, 2009; Cohen et al., 2012, 2015; Pessenda et al., 2012; França et al., 2014, 2016; Fontes et al., 2017) during the Holocene. Coastal wetlands have the ability to maintain stability with sea-level (Kirwan and Murray, 2007). Equilibrium models of coastal wetlands consider several feedbacks that allow the coastal wetlands to keep their locations relative to the tidal range (Cohen et al., 2005; McKee et al., 2007), where sediment vertical accretion increases according to a depth of tidal flood (French and Stoddart, 1992; Furukawa and Wolanski, 1996; Blasco et al., 1996; Cahoon et al., 1997; Krauss et al., 2013), and availability of accommodation space (Boyd et al., 1981; Woodroffe, 2002; Job

71 et al., 2021), which allows the wetland to keep pace with relative sea level (Cahoon et al.,

72 2006).

73   Mangroves occur parallel to the coastline, with zonations characterized by species

74 dominating tidal flats more exposed to marine influence. Other species occupy higher

75 tidal flats as a response to the substrate physical-chemical characteristics (Snedaker,

76 1982; Hutchings and Saenger, 1987). For instance, several mangrove tree species reach

77 an ideal development at salinities between 5 and 25 ‰ (Burchett et al., 1989; Ball and

78 Pidsley, 1995; Suárez and Medina, 2005) and respond to coastal processes and sediment

79 deposition (França et al., 2012). *Rhizophora mangle* dominates on unstable tidal flats

80 exposed to direct tidal influence. By contrast, *Avicennia germinans* dominates the higher

81 tidal flats subjected to higher porewater salinities, and *Laguncularia racemosa* is

82 commonly found in less saline environments and sandy sediments (Hogarth, 2007).

83 Therefore, mangroves occur along environmental gradients characterized by salinity,

84 landforms, and sediment types, which reflect fluvio-marine dynamics (Thom, 1984;

85 Woodroffe, 1992).

86   The Doce River delta, southeastern Brazil, is considered one of the largest wave-

87 dominated deltas of Brazil (Suguio et al., 1980; Dominguez et al., 1981; Martin et al.,

88 1996). The delta progradation occurred during the last 5000 cal yr BP according to the

89 late Holocene marine regression. The delta development occurred by beach ridge

90 progradation according to a relative sea-level fall during the middle and late Holocene

91 (Angulo et al., 2006; Cohen et al., 2020; Toniolo et al., 2020). Thus, a relative sea-level

92 fall may cause a seaward mangrove migration due to changes in flow energy and tidal

93 inundation frequency (Cohen and Lara, 2003).

94

95   Mangroves expanded upstream of the Doce River delta, during the early-middle

96   Holocene, followed by contraction and eventual disappearance of this ecosystem during

97   the late Holocene (Buso Junior et al., 2013; França et al., 2013). The edges of the estuaries

98   and tidal creeks are occupied by species typical of mangrove forests (Bernini et al., 2006).

99   However, those works did not directly show the dominant plants along the Doce River

100   estuary during the late Holocene. Therefore, it remains unclear when the mangrove types

101   began to grow and the meaning of mangrove type succession. Mangroves may be resilient

102   to sea-level fluctuations, but few works provided evidence about the relationship between

103   the mangrove type succession and stressors factors, such as sea-level changes.

104   Then, how does each mangrove type respond to changes in depositional

105   environments, controlled by sea-level fluctuations and input of different sediment grain

106   sizes? It is a subject still open for discussion. Therefore, to contribute to the discussion

107   and understanding of the mangrove resilience to changes in a wave-influenced delta

108   (Southeastern Brazil) during the late Holocene, this paper presents the integration of

109   multi-proxy data with sedimentary facies, pollen, isotopes (δ^{13}C, δ^{15}N) and elemental

110   analysis.

111

112   **2. Modern settings**

113   *2.1. Study area and geological setting*

114   The study sites are located between 40º 04'– 39º 40' W and 18º 34'– 19º 48' S and are

115   adjacent to two river mouths, the Barra Seca River (sediment core MBN) and the São

116   Mateus River (sediment core LI-34; reviewed in this work; França et al., 2016), which

117   are each part of the Doce River Delta, State of Espírito Santo, southeastern Brazil (Fig.

118   1). The Holocene sedimentary dynamic in the study area is mainly controlled by relative

119   sea-level change (RSL), fluvial sediment supply, and longshore currents. The formation

120   of a barrier island/lagoonal system began at about 7000 cal yr BP (Suguio et al., 1982;

121   Martin et al., 1996, 2003).

122   The region is mainly represented by the Barreiras Formation formed by

123   continental and transitional deposits, with many broad valleys (Martin et al., 1996;

124   Rossetti et al., 2013). Four geomorphological units may be identified in the study area:

125   (1) a mountainous province with Precambrian rocks; (2) a tableland area, comprising the

126   Barreiras Formation, gently sloping toward the coast, composed of sandstones,

127   conglomerates and mudstones – attributed to Neogene marine transgressions

128   (Dominguez et al., 2009; Rossetti et al., 2013); (3) a coastal plain area, with fluvial,

129   transitional and shallow marine sediments, accumulated during RSL changes (Martin and

130   Suguio, 1992); and (4) an inner continental shelf area with surficial sediments composed

131   mainly by fine to coarse sands and mud sediments.

132

133   *2.2. Modern climate and oceanography*

134   The study area is located in a warm and humid tropical climate, with annual precipitation

135   ~1190 mm and temperature ranges between 20º and 26º C (Buso-Junior et al., 2013).

136   Precipitation occurs mainly during the summer (November – January), while the winter

137   is characterized by a dry season (May – September), regulated by the Intertropical

138   Convergence Zone (ITCZ) and the position of the South Atlantic Convergence Zone

139   (SACZ) (Carvalho et al., 2004). The study area is affected by the South Atlantic trade

140   winds belt (NE-E-SE) under the influence of a local high-pressure cell and the episodic

141   advance of the Atlantic Polar Front, causing SSE winds (Dominguez et al., 1992; Martin

142   et al., 1998).

143   The coastal plain of the Doce River has a maximum width of about 40 km and

144   length of about 150 km (Bittencourt et al., 2007). This region is influenced by the Atlantic

145   Ocean with microtidal semidiurnal, ranging below 2 m. The tidal water salinity is between

146   9 and 34‰. The Doce River has a maximum and minimum outflow of ~1900 and ~400

147   m^3/s, while the São Mateus River has a discharge ~11 m^3/s (Bernini et al., 2006).

148

149   *2.3. Modern vegetation*

150   Most of the study area is occupied by mangrove trees, ~5-10 m tall, represented by

151   *Rhizophora mangle*, *Laguncularia racemosa,* and *Avicennia germinans*. *Rhizophora* and

152   *Laguncularia* trees occur mainly along the channels, while *A. germinans* grows mainly

153   on higher tidal flats. Nowadays, mangrove forests are restricted to the northern sector of

154   the Doce River Delta (Bernini et al., 2006), including the mouths of Barra Seca and São

155   Mateus Rivers. The sandy coastal plain flora includes *Ipomoea pes-caprae*, *Hancornia*

156   *speciosa*, *Chrysobalanus icaco*, *Hirtella americana, Cereus fernambucensis* and palm

157   trees. It is also characterized by pioneering freshwater plants such as *Hypolytrum* sp.,

158   *Panicum* sp, and brackish water plants such as *Polygala cyparissias*, *Remiria maritima*,

159   *Typha* sp., *Cyperus* sp., *Montrichardia* sp., *Tapirira guianensis*, and *Symphonia*

160   *globulifera*. Herbaceous vegetation is also found at the coastal plain, represented by

161   Araceae, Cyperaceae, and Poaceae. Tropical rainforest, occupying higher ground further

162   inland, is predominantly characterized by the following families: Annonaceae, Fabaceae,

163   Myrtaceae, Sapotaceae, Bignoniaceae, Lauraceae, Hippocrateaceae, Euphorbiaceae, and

164   Apocynaceae (Peixoto and Gentry, 1990).

165

166   **3. Materials and methods**

167   *3.1. Fieldwork and sampling processing*

168   For the description of the geological characteristics, the SPRING 3.6.03 processing

169   system was used, which generated an image of composition RGB 543, elaborated from a

170   LANDSAT 7 image, obtained in July 2011 from the Brazilian National Research Institute

171   (INPE). Global Mapper 12 software was used to generate the topographic map, based on

172   SRTM-90 data (http://srtm.usgs.gov/data/obtainingdata.html).

173   The sediment cores MBN (4.95 m depth, S 18º58'31.3" / W 039º44'36.0" and

174   0.6 m elevation – Barra Nova estuary) and LI-34 (4 m depth, S 18°36'27.4"/ W

175   39°44'40.4" and 1 m elevation – São Mateus estuary) were retrieved from a mangrove

176   muddy tidal flat (Fig. 1) using a Russian Peat sampler (USEPA, 1999). This area is a

177   southeastern wave-dominated coast and has micro-tidal influence (Dominguez et al.,

178   2009). Mean spring tidal range is 1.7 m in the area. The geographical positions of the

179   cores were determined by GPS (Reference Datum: SAD69).

180

181   *3.2. Radiocarbon dating*

182   Based on stratigraphic discontinuities, suggested by color, lithology, and texture, seven

183   bulk samples (10 g each) were chosen for radiocarbon analysis. The sediments were

184   verified and physically cleaned under a stereomicroscope. Samples were placed in 2%

185   HCl at 60°C for 4 hours to eliminate adsorbed carbonates. These samples were also rinsed

186   and dried at 50 ºC, following procedures described in Pessenda et al. (2012). The

187   chronological context for the studied stratigraphic sequence was supplied by an

188   accelerator mass spectrometer (AMS) radiocarbon dating at the [14]C Laboratory of

189   Fluminense Federal University (LACUFF) and at UGAMS (University of Georgia –

190   Center for Applied Isotope Studies). Radiocarbon ages were normalized to a $\delta^{13}C$ of -

191 25‰ VPDB and reported as calibrated years (cal yr BP) (2σ) using CALIB 7.1 (Stuiver

192 et al., 2018 - http://calib.org – accessed 2019-5-27). The dates (Table 1) are presented in

193 the text as the median of the range of calibrated ages based on IntCal13 (Reimer et al.,

194 2013).

195

196 *3.3. Facies description*

197 The cores were X-rayed to identify sedimentary structures and transported to the

198 Laboratory of Chemical Oceanography/UFPA. The sediment grain size distribution was

199 determined by laser diffraction using a Laser Particle Size SHIMADZU SALD 2101. The

200 sediment grain size was based on the Wentworth (1922) with sand (2-0.0625 μm), silt

201 (62.5-3.9 µm), and clay fractions (3.9-0.12 µm). Facies analysis involved description of

202 color (Munsell Color, 2009), lithology, texture, and structure (Harper, 1984; Walker,

203 1992). The sedimentary facies codes followed Miall (1978).

204

205 *3.4. Palynological analysis*

206 Sediment samples (1.0 cm^3) were taken at 10 cm intervals and processed by standard

207 pollen analytical techniques (Faegri and Iversen, 1989). This sampling interval along

208 cores with 4 – 5 m long sampled from tidal flats with sedimentation rates between 1 and

209 20 mm/yr is appropriate for a palaeoenvironmental reconstruction during the late

210 Holocene (Behling et al., 2004; Cohen et al., 2012; França et al., 2013). Pollen and spores

211 were categorized according to the reference collections of about 4,000 Brazilian flora taxa

212 (Salgado-Labouriau, 1973; Markgraf and D'Antoni, 1978; Roubik and Moreno, 1991;

213 Colinvaux et al., 1999) jointly with the reference collection of the Laboratory of Coastal

214 Dynamics – Federal University of Pará and [14]C Laboratory of the Center for Nuclear

215   Energy in Agriculture (CENA/USP). At least 300 terrestrial pollen grains were counted

216   for each sample. The total terrestrial pollen sum excludes fern spores and aquatic pollen.

217   Results were expressed as percentages of the total terrestrial pollen sum. The

218   classification pollen taxa were based on pollen source: mangroves, trees and shrubs,

219   palms, and herbs pollen. TILIA and TILIAGRAPH was used for calculations and

220   graphical plotting (Grimm, 1990). The cluster analysis of pollen taxa was developed by

221   CONISS (Grimm, 1987).

222

223   *3.5. Isotopic and chemical analysis*

224   Sediment samples (6-50 mg) were obtained along the cores at 10 cm intervals, and 2%

225   HCl was used to remove carbonate. It was washed with distilled water until the pH

226   reached 6, and dried at 50°C. The sediment samples were analysed for total organic

227   carbon, nitrogen, and sulfur at the Stable Isotopes Laboratory and at the Nutrient Cycling

228   Laboratory of the Center for Nuclear Energy in Agriculture (CENA/USP). Samples were

229   analyzed in an ANCA SL2020 mass spectrometer and Sulfur Analyzer SC 144DR-LECO,

230   respectively. The values are represented as a percentage of dry weight, with an analytical

231   precision of 0.09% (TOC) and 0.07% (TN), respectively. The standard for sulfur analysis

232   was 0.031% (dry soil), from 0.028 to 0.034% (mean values). The ^{13}C and ^{15}N results are

233   expressed as δ^{13}C and δ^{15}N with respect to VPDB standard and atmospheric air.

234   Analytical precision is ±0.2‰ (Pessenda et al., 2004). In order to describe and understand

235   the source of organic matter, the binary analyses between δ^{13}C vs. C:N (Meyers, 2003;

236   Wilson et al., 2005; Lamb et al., 2006) and δ^{15}N vs. δ^{13}C (Peterson and Howarth, 1987;

237   Fellerhoff et al., 2003) were used. Leaves of the vegetation units were sampled for

238   isotopic δ^{13}C determination.

239

4. Results

4.1. Radiocarbon dating

The data presented in Table 1 provide late Holocene chronological control since ~2660 cal yr BP (core MBN, 4.79-4.77 m depth). The ^{14}C dates revealed that studied sediments were deposited according to a vertical accretion range between 0.45 and 20.07 mm/yr typical for the studied coast (16 – 1 mm/yr) during the mid-late Holocene. The high sedimentation rates have been attributed to a higher sediment accommodation space during the mid-late Holocene, caused by the middle Holocene high sea-level stand (Breithaupt et al., 2012, 2018; França et al., 2013, 2015, 2016; Lorente et al., 2014; Cohen et al., 2020). In this work we have used the informal terms mid and late Holocene instead of Middle or Late Holocene. The Quaternary literature has used variable informal usage of 'early', 'middle' or 'mid', and 'late' with the beginning of the middle Holocene ranges in age from 8 to 6 ka BP, while the end of the middle Holocene varies between 5 and 2.5 ka BP (e.g. Hoguin and Restifo, 2012). Walker et al., (2012) proposed an Early–Middle Holocene boundary at 8200 a BP and a Middle–Late Holocene boundary at 4200 a BP. However, proposal for relative sea-level changes for the Brazilian coast have used an informal scale for the Holocene (Angulo et al., 2006, 2016). Therefore, to discuss the temporal correlations of the events identified in this work with the relative sea-level changes proposed for the Brazilian coast, we decided to keep the Holocene informal scale for this work.

260

261

4.2. $\delta^{13}C$ values of modern vegetation

263   Thirty-two species of the most abundant plants were collected at the study sites. The δ^{13}C

264   values range between -30.10‰ and -11.48‰, indicating dominance of C$_3$ plants (Table

265   2). C$_4$ plants are restricted to the Poaceae family (*Paspalum* sp. and *Sporobolus*

266   *virginicus*). Some species were characterized as CAM (Ecophysiology of Crassulacean

267   Acid Metabolism), such as Cactaceae (*Cereus fernambucensis*) and Clusiaceae (*Clusia*

268   *nemorosa*).

269

270   *4.3. Facies associations*

271   The sediment cores were comprised of mostly greenish-gray or dark brown muddy and

272   sandy silts (Fig. 2 and Fig. 3). The cores are characterized by massive sand (facies Sm),

273   sand with cross-laminations (facies Sc), parallel lamination sand (facies Sp), lenticular

274   (facies Hl), wavy (facies Hw), flaser (facies Hf) heterolithic bedding, and parallel

275   laminated mud (facies Mp) with convolute lamination. Additionally, bioturbation

276   structures, characterized by benthic tubes, plant remains, shells, roots, and root marks are

277   present. Evaluation of sediment texture and structure and associated pollen and isotopic

278   data (δ^{13}C and δ^{15}N), together with C:N and C:S values, revealed three facies associations

279   which represent a typical tidal flat setting, characterized by an estuarine point bar (facies

280   association A), tidal flat with mangrove/herbs vegetation (facies association B), and

281   estuarine channel (facies association C).

282

283   *4.3.1. Facies association A (estuarine point bar)*

284   The facies association A only occurs in core MBN between ~2660 and ~2215 cal yr BP

285   (Fig. 2), between 4.9 and 3.8 m depth. It mainly consists of lenticular heterolithic bedding

286   (facies Hl) with basal sand cross-lamination (facies Sc) and parallel sand lamination

287 (facies Sp). Close to the top of this facies association inclined wavy (Hw) and flaser (Hf)

288 heterolithic bedding with mud and organic matter deposition are present, which reflects

289 point-bar lateral accretion within a meandering creek (Thomas et al., 1987).

290 The pollen record mainly shows an increase of herbaceous pollen (Fig. 4),

291 between 2660 and 2215 cal yr BP (beginning of zone I), such as Poaceae (15-60%),

292 Cyperaceae (5-15%), Asteraceae (2-4%), *Borreria* (<2%), and Convolvulaceae (<2%).

293 Other ecological groups show a decreasing trend. Trees and shrubs are mainly

294 characterized by Fabaceae (2-24%), Euphorbiaceae (5-15%), Rubiaceae (5-10%),

295 Apocynaceae (3-7%), Moraceae (2-7%), *Mimosa* (2-5%), and *Alchornea* (~10%) pollen

296 grains close to the top of this facies association. Palm pollen ranges between 5% and 16%.

297 Mangrove pollen ranges between 5% and 16% abundance, mainly characterized by

298 *Rhizophora* (3-6%), *Laguncularia* (5-16%), and *Avicennia* (<5%).

299 The δ^{13}C and C:N values oscillate between -27‰ and -17‰ ($\bar{x}$ = -23‰), and 12

300 and 45 ($\bar{x}$ = 27.5) between 4.9 and 3.8 m depth, respectively (Fig. 2). δ^{15}N values range

301 between 2.8‰ and 9.3‰ ($\bar{x}$ = 6.2‰) and the C:S ratio ranges between 0.38 and 5.18 ($\bar{x}$

302 = 2).

303

304 *4.3.2. Facies association B (tidal flat with mangrove/herbs vegetation)*

305 This association was identified in core MBN from 3.7 m depth to the surface (~2215 cal

306 yr BP; Fig. 2) and LI-34 from 3.7 m depth to the surface (~1340 cal yr BP; Fig. 3). The

307 facies association B is largely comprised of mud with fine and very fine sand, lenticular

308 heterolothic bedding (facies Hl), massive sand deposits (facies Sm), flaser bedding (facies

309 Sf), cross-lamination sand (facies Sc), and parallel laminated mud bedding (facies SMh).

310 This deposit also contains benthic tubes, shells fragments, root, and root marks.

311   The pollen assemblage of facies association B is mainly characterized by

312 herbaceous pollen, but trees, shrubs, palms, and mangrove pollen are also present (Fig. 4

313 and Fig. 5). The herbaceous pollen is mainly characterized by Poaceae (7-70%),

314 Cyperaceae (4-30%), Amaranthaceae (2-50%), *Borreria* (1-14%), Asteraceae (3-11%),

315 Malvaceae (1-5 %), and *Smilax* (1-6%). The most common tree and shrub taxa are:

316 *Alchornea* (5-50%), Fabaceae (2-50%), Rubiaceae (2-45%), Euphorbiaceae (5-20%),

317 Moraceae (2-15%), *Mimosa* (2-8%), Malpighiaceae (5-7%), Apocynaceae (2-6%),

318 *Cecropia* (2-6%), Myrtaceae (2-6%), and Anacardiaceae (2-5%), together with low

319 percentage abundance (<5%) of *Croton*, Meliaceae, and Sapindaceae. Aquatic taxa

320 consist of *Typha* (10%), and palms (Arecaceae) range from 2-55% abundance. Mangrove

321 pollen assemblages are characterized by *Avicennia*, *Laguncularia,* and *Rhizophora* in

322 core MBN (4-25%), and *Avicennia* and *Rhizophora* in core LI-34 (5-37%). In the core

323 MBN a mangrove intra-species variation with the disappearance of *Avicennia* and

324 *Rhizophora* occurred near 1.5 m, between ~2215 and ~2075 cal yr BP, while

325 *Laguncularia* pollen was present to the surface. The surface-core pollen assemblage had

326 low abundance of *Rhizophora* pollen (1-2%) (Fig. 4). In contrast, in core LI-34,

327 *Rhizophora* pollen is present in the record since at least 900 yr BP (2.0 m), and *Avicennia*

328 is present since 360 cal yr BP (1.5 m) (Fig. 5).

329    $\delta^{13}C$ values range between -31‰ and -11.5‰ ($\overline{x}$ = -23.3‰), while $\delta^{15}N$ values

330 range between 1.3‰ and 14.5‰ ($\overline{x}$ = 4.8‰). C:N ratios range between 5.96 and 45.5 ($\overline{x}$

331 = 20.8) and C:S ratios (MBN core) range between 0.02 and 3.65 ($\overline{x}$ = 2.05).

332

333 *4.3.3. Facies association C (estuarine channel)*

14

334 The facies association C was only identified at the base of core LI-34 (~1340 cal yr BP)

335 (Fig. 3 and 5), between 4.0 and 3.7 m, which consists of a massive sand deposit (facies

336 Sm) with fine to medium-grained sediments and shell fragments.

337   Pollen analysis indicated the predominance of herbaceous pollen (Fig. 5), such

338 as Poaceae (44-56%), Cyperaceae (41-49%), Amaranthaceae (3-6%), Asteraceae, and

339 *Borreria* (~2%) (Fig. 5). The δ^{13}C values vary between -31 and -27‰. The δ^{15}N values

340 oscillate between 4 and 6‰. The TOC and nitrogen values are relatively low at the bottom

341 of the core (0.1-0.2% and ~0.01%, respectively). C:N ratios range between 12 and 15

342 (Fig. 3).

343

344 **5. Interpretation and discussion**

345 *5.1. Paleoenvironmental reconstruction*

346 The multi-proxy data reveal three environmental phases spanning the last ~2660 cal yr

347 BP, based on changes in RSL and sediment supply (Fig. 6). The first phase, between

348 ~2660 and ~2050 cal yr BP, is mainly marked by the presence of *Rhizophora,*

349 *Laguncularia,* and *Avicennia* on point bar deposits inland (Figs. 2 and 6). The second

350 phase, between ~2050 and ~900 cal yr BP, is marked by the disappearance of *Avicennia*

351 and *Rhizophora* from the MBN site. During the last ~900 cal yr BP, the third phase is

352 marked by extensive expansion of *Laguncularia* mangroves on tidal flats upriver and the

353 presence of *Rhizophora* mangroves giving way to *Avicennia* mangroves at the mouth of

354 the São Mateus River (core LI-34).

355

356 *5.1.1. Phase 1 (~2660 to ~2050 cal yr BP)*

357   This phase is marked by sand and mud massive sediments, followed by parallel laminated

358   mud/sand with bioturbation structures. It is indicative of both high and low energy flow.

359   These sedimentary features, together with the pollen and geochemical characteristics,

360   suggest the development of a point bar and presence of herbaceous plants and mangrove

361   trees, represented by *Avicennia, Laguncularia,* and *Rhizophora* since at least ~2660 cal

362   yr BP, behind the late Holocene beach ridges. During this phase there was a transition

363   from a point bar to a tidal flat. The end of this phase is marked by the disappearance of

364   *Avicennia* and *Rhizophora* mangrove taxa around 2075 cal yr BP, with only *Laguncularia*

365   mangrove trees remaining. The latter was likely caused by channel migration and a

366   decrease in sea-level, leading to an increase in erosion. Therefore, a common zonation

367   from the intertidal fringe to higher elevations landward indicates the following genus

368   mangrove gradient: *Rhizophora > Avicennia > Laguncularia* (Woodroffe, 1982).

369   Furthermore, the decrease in *Rhizophora* and *Avicennia* trees, leaving only *Laguncularia*

370   trees, which commonly occupy less saline environments (Hogarth, 2007), indicates a

371   reduction in salinity, probably due to a sea-level drop and/or to the wet climate. In

372   addition, *Laguncularia* trees have greater resilience to adverse conditions (Tomlinson,

373   1986; Gu et al., 2019; Cohen et al., 2020). We interpret this sequence of mangrove

374   dynamics to signify relative sea-level fall over the last 5500 cal yr BP, which led to an

375   increase in sediment supply (França et al., 2016). Locally, the establishment of mangroves

376   depends on the dynamics of channel migration. The relationship between $\delta^{13}C$ values,

377   ranging from -27 and -16‰, and C:N ratios (12-45), indicates that sedimentary organic

378   matter was sourced from mixing between C_3 terrestrial plants and marine dissolved

379   organic carbon-DOC (Fig. 7), suggesting estuarine zones between ~2660 and ~2050 cal

380   yr BP.

381

5.1.2. Phase 2 (~2050 to ~900 cal yr BP)

During this phase a mangrove succession developed, whereby the mangrove community

of preceding phase 1, containing a mix of *Avicennia, Rhizophora*, and *Laguncularia* trees,

was replaced by a monospecific mangrove community dominated by *Laguncularia* trees

at the MBN site. Tidal flats constitute favorable hydrodynamic conditions for mangrove

development due to muddy sedimentation, with low-energy waves and low current

velocity. During this phase, oscillations in wave energy and velocity produced cross-

lamination sand, inducing the migration of small sand ripples (Reineck and Singh, 1980).

Furthermore, the upward fineing sequence indicates a decrease in energy flow, favouring

the establishment of a tidal flat, with sedimentation rates around 20 mm/yr. These

hydrodynamic conditions favored mangrove development.

During this phase $\delta^{13}C$ values ranging between -28 and -22‰, together with C:N

ratios between 6 and 40, indicate that organic matter was sourced predominantly from C_3

plants ($\delta^{13}C$: -32‰ to -21‰, C:N >20; Deines, 1980) (Fig. 2, MBN core). An estuarine

environment is consistent with $\delta^{13}C$ values ranging from -32‰ to -26‰, and C:N ratios

from < 25 to >6, according to figure 7 (Lamb et al., 2006). The $\delta^{15}N$ values between 4

and 7.4‰ ($\bar{x}$ = 5.8‰) suggest a mixture of terrestrial plants and aquatic organic matter

(Sukigara and Saino, 2005). The trends of rising carbon and nitrogen values signify

mangrove establishment.

5.1.3. Phase 3 (900 cal yr BP until present)

This phase is marked by the abundance of *Laguncularia* and *Rhizophora* trees occupying

upriver tidal flats at the MBN site, as well as the presence of a mangrove ecosystem

405   dominated by *Rhizophora* and *Avicennia, and some Laguncularia (<3%)*, on tidal flats

406   near the mouth of the São Mateus River at the LI-34 site (Fig. 6). The sediments are

407   characterized by heterolithic bedding and massive sand, with plant remains and rootlets.

408   At the LI-34 site, near the São Mateus River mouth, this phase is marked by sand

409   deposition, typical of the mouth of an estuarine channel. Following a sea level decrease,

410   relative sea-level stabilized (Angulo et al., 2006). This favoured mangrove establishment,

411   characterized by *Rhizophora* and *Avicennia,* around 900 cal yr BP at the LI-34 site and

412   mangrove migration to the mouth of the São Mateus River.

413   According to the δ^{13}C values (around -28‰), and C:N ratios (16-27), tidal flats

414   close to the mouth of the Barra Seca and São Mateus River were characterized by C_3

415   terrestrial plants and a mixture of freshwater/estuarine dissolved organic carbon (DOC)

416   (Fig. 7), consistent with a marine influence and mangrove colonization.

417

418   *5.2. Floristic changes to mangrove communities*

419   Mangroves expanded upstream of the Doce River delta, southeastern Brazil, during the

420   early-middle Holocene, and were occupying topographically higher flats in the mid-

421   Holocene (França et al., 2015). However, the RSL fall combined with the higher sediment

422   fluvial discharge caused a coastal progradation over the last ~6350 cal yr (Buso Junior et

423   al., 2013; França et al., 2013, 2016; Lorente et al., 2014). According to our data,

424   mangroves migrated to lower tidal flats behind the current beach ridges between ~2660

425   and ~900 cal yr BP due to sea-level drop. The stabilization of relative sea-level during

426   the last 900 cal yr BP contributed to the development of tidal flats and mangrove

427   expansion, with a predominance of *Laguncularia* mangroves upstream and the

428   establishment of *Rhizophora/Avicennia* mangroves at the mouth of the rivers.

429   Mangrove species differ in their responses to local environmental conditions,

430 which directly affect their development (Tomlinson, 1986). These environmental

431 variations may drive either positive or negative feedback, depending on the taxon. For

432 example, salinity variations may impair the growth and reproduction of certain mangrove

433 species, such as *Avicennia* (Naidoo et al., 2011). On the other hand, an increase in salinity

434 can drive an increase in the production of chlorophyll-*a* and b in *Laguncularia racemosa*

435 (Sobrado, 2000), giving it greater resistance to adverse conditions and increasing its

436 colonization potential. It is important to emphasize that, unlike *Rhizophora*, both

437 *Laguncularia* and *Avicennia* are adapted to hypersalinity conditions. However, for

438 successful germination, *Laguncularia* can withstand longer periods of salinity than

439 *Avicennia* (Cavalcanti et al., 2007), which means that *Laguncularia* is relatively better

440 adapted for growth in the middle of the spatial-temporal salinity spectrum and,

441 accordingly, has higher plasticity (Tomlinson, 1986). Furthermore, the increase in flow

442 energy, evidenced by the deposition of sandy sediments, may also contribute to mangrove

443 community changes, leading to species turnover (França et al., 2012). For example,

444 *Laguncularia* is commonly found in more disturbed environments than those of

445 *Rhizophora* and *Avicennia* (Hogarth, 2007), and may withstand the impact caused by

446 disasters and/or human pollution, such as metal contamination at the Doce River estuary

447 after the dam collapse on 5th November 2015 (Fernandes et al., 2016). On the sand bars,

448 coastal dynamics caused high mangrove mortality by erosion or sand sedimentation on

449 mangrove muddy substrates, which have caused tree roots to suffer from anoxia (Gil-

450 Torres and Ulloa-Delgado, 2001). Mangroves dominated by *Rhizophora* retreated along

451 the northern Brazilian coastline due to landward sand migration that covered the mudflat

452 and asphyxiated vegetation (Cohen and Lara, 2003; França et al., 2012).

453   The ecophysiological characteristics of *Laguncularia racemosa* highlight its

454   important role as a pioneer species in mangrove succession; e.g. creating suitable

455   microclimatic conditions (raising humidity and reducing soil temperature) to facilitate

456   colonization by other mangrove tree species (Cavalcanti et al., 2007). Thus, mangroves

457   have demonstrated considerable resilience over timescales commensurate with shoreline

458   evolution, resisting natural disturbances, and human impacts (Alongi, 2008).

459   Our multi-proxy late Holocene records show that, by the end of the first phase

460   (2075 cal yr BP), populations of *Avicennia* and *Rhizophora* had decreased substantially,

461   with only *Laguncularia* remaining in the area near the Barra Seca River mouth. We argue

462   that these floristic changes were most likely caused by relative sea-level fall and channel

463   migrations. These processes triggered successive changes in the salinity and grain size of

464   the sedimentary environment, thus destabilizing the system. According to Kathiresan and

465   Thangam (1990), fluctuations in the environment salinity have a more relevant effect on

466   mangrove species than a constant hypersalinity. Once a mangrove forest is established,

467   successive changes in salinity can lead to the death of adult individuals as they have less

468   plasticity than seedlings. This effect was observed in situations where there were changes

469   in the flood dynamics caused by changes in the mouth of a river (Tognella et al., 2006).

470   Our sedimentary profiles show that our study area experienced high energy in several

471   periods due to the presence of laminations of sand from the base towards the top of the

472   core, suggesting signifying fluctuations in the environment salinity. These variations

473   would have driven the disappearance of the genera *Avicennia* and *Rhizophora* from the

474   region near the Barra Seca River mouth. In contrast, the pioneer tree *Laguncularia* would

475   have been resilient to these salinity variations. In the upper part of the MBN core (phase

476   3), no sandy deposition pulses were observed, thus indicating a possible stabilization in

477   the system, which together with the decrease in RSL and greater continental influence,

478   decreased the salinity of the environment and allowed the reappearance of individuals of

479   *Rhizophora*.

480

481   **6. Conclusions**

482   This paper's multi-proxy data reveal the mangrove response to the relative sea-level fall

483   and sedimentary dynamics of the Doce River Delta region of Espírito Santo state,

484   southeastern Brazil in the late Holocene. Our results show that the mangrove may be

485   resilient to Atlantic sea-level fluctuations, but that the previous floristic composition of

486   the mangrove vegetation differed from what is currently present. Therefore, this study

487   resolves a key research question of widespread interest, revealing the mangrove response

488   to the sediment dynamics and sea-level fluctuations. Thus, mangrove ecosystems have

489   existed in the current coastal zone since at least ~2660 cal yr BP, with a dynamic history

490   which comprises three phases: 1°) an estuarine point bar/tidal flat with mixed mangroves

491   (~2660 until ~2050 cal yr BP), 2°) a tidal flat with *Laguncularia* mangroves (~2050 until

492   ~900 cal yr BP), and 3°) tidal flats with *Laguncularia* mangroves upstream and

493   establishment of *Rhizophora/Avicennia* mangroves at the mouth of the rivers (~900 cal

494   yr BP until present). The geochemical results indicate a dominance of C_3 terrestrial plants

495   with some influence of C_4 plants and organic matter of marine/estuarine origin along the

496   studied cores. The pollen data show that the mangroves in this region have been present

497   since at least ~2660 cal yr BP. *Laguncularia* and *Rhizophora* trees were the initial

498   pioneers in mangrove development, followed by *Avicennia*. Currently, mangroves in the

499   MBN area (Barra Nova estuary) are dominated by *Laguncularia. Rhizophora/Avicennia*

500   mangroves occur at the mouth of the rivers. Therefore, our data reveal changes in the

501 mangrove ecosystem due to a gradual relative sea-level fall during the late Holocene and

502 the sedimentary dynamics which resulted in the development of tidal flats and a mangrove

503 succession. The succession from a mixed mangrove community (*Rhizophora*,

504 *Laguncularia*, and *Avicennia*) to a monospecific mangrove community comprised only

505 of *Laguncularia* is likely due to differing tolerances of these taxa to variations in salinity,

506 sediment deposition associated with changes in sea-level and channel dynamics, and

507 immediate impact caused by disasters and/or human pollution.

508

519

520 **References**

521 Alongi, D., 2008. Mangrove forests: Resilience, protection from tsunamis, and respondes

522   to global climate change. Estuarine, Costal and Shelf Science 76 (1), 1-13.

523   Amaral, P.G.C., Ledru, M.P., Branco, F.R., Giannini, P.C.F., 2006. Late Holocene

524   development of a mangrove ecosystem in southeastern Brazil (Itanhaém, state of São

525   Paulo). Palaeogeogr. Palaeoclimatol. Palaeoecol. 241 (3), 608-620.

526   Angulo, R.J., Lessa, G.C., Souza, M.C., 2006. A critical review of Mid- to Late-Holocene

527   sea-level fluctuations on the eastern Brazilian coastline. Quaternary Science Reviews

528   25, 486-506.

529   Angulo, R.J., De Souza, M.C., Assine, M.L., Pessenda, L.C.R., Disaró, S.T., 2008.

530   Chronostratigraphy and radiocarbon age inversion in the Holocene regressive barrier

531   of Paraná, southern Brazil. Marine Geology 252, 111-119.

532   Angulo, R.J., Giannini, P.C.F., Souza, M.C. De, Lessa, G.C., Angulo, R.J., Giannini,

533   P.C.F., Souza, M.C. De, Lessa, G.C., 2016. Holocene paleo-sea level changes along

534   the coast of Rio de Janeiro, southern Brazil: Comment on Castro et al. (2014). An.

535   Acad. Bras. Cienc. 88, 2105–2111.

536   Ball, M.C., Pidsley, S.M., 1995. Growth responses to salinity in relation to distribution

537   of two mangrove species, *Sonneratia alba* and *S. lanceolata*, in northern Australia.

538   Funct. Ecol. 9, 77-85.

539   Behling H, Cohen M.L, Lara R., 2004. Late Holocene mangrove dynamics of Marajó

540   Island in Amazonia, northern Brazil. Vegetat. Hist. and Archaeobot. 13, 73-80.

541   Bernini, E.S.M.A., Carmo T.M., Cuzzuol, G.R.F., 2006. Composição química do

542   sedimento e de folhas das espécies do manguezal do estuário do rio São Mateus,

543   Espírito Santo, Brasil. Rev. Bras. Bot. 29, 686- 699.

544   Bittencourt, A.C.S.P., Dominguez, J.M.L., Martin, L., Silva, I.R., De-Medeiros, K.O.P.,

545   2007. Past and current sediment dispersion pattern estimates through numerical

546   modeling of wave climate: an example of the Holocene delta of the Doce River,

547   Espírito Santo, Brazil. Anais da Academia Brasileira de Ciências 79, 333-341.

548 Blasco, F., Saenger, P., Janodet, E., 1996. Mangrove as indicators of coastal change.

549   Catena 27, 167-178.

550 Breithaupt, J., Smoak, J., Smith, T., Sanders, C., Hoare, A., 2012. Organic carbon burial

551   rates in mangrove sediments: Strengthening the global budget. Global Biogeochemical

552   Cycles 26 (3), 1-11.

553 Breithaupt, J., Smoak, J., Byrne, R., Waters, M., Moyer, R., Sanders, C., 2018. Avoiding

554   timescale bias in assessments of coastal wetland vertical change. Limnology and

555   Oceanography 63 (S1), 477-495.

556 Boyd. R., Penland, S., 1981. Washover of deltaic barriers on the Lousiana coast. Trans.

557   Gulf Coast Assoc. Geol. Socs. 31, 243-248.

558 Burchett, M.D., Clarke, C.J., Field, C.D., Pulkownik, A., 1989. Growth and respiration

559   in two mangrove species at a ranges of salinities. Physiol. Plant.75, 299-303.

560 Buso Junior, A.A., Pessenda L.C.R., Oliveira P.E.O., Giannini P.C.F., Cohen M.C.L.,

561   Ribeiro C.V., Oliveira S.M.B., Favaro D.I.T., Rossetti D.F., Lorente F.L., Borotti

562   Filho M.A., Schiavo J.A., Bendassolli J.A., França M.C., Guimaraes J.T.F., Siqueira

563   G.S., 2013. Late Pleistocene and Holocene Vegetation, Climate Dynamics,and

564   Amazonian taxa in the Atlantic Rainforest of Linhares, Southeastern Brazil.

565   Radiocarb. 55, 1747- 1762.

566 Bush, M.B., Colinvaux, P.A., 1990. A long record of climatic and vegetation change in

567   lowland Panamá. Journ. of Veget. Scien., Uppsala 1, 105-118.

568 Bush, A.M., Bambach, R.K. & Daley, G.M., 2007. Changes in theoretical ecospace

569   utilization in marine fossil assemblages between the mid-Paleozoic and late Cenozoic.

570   Paleobiol. 33, 76-97.

571 Cahoon, D.R, Lynch, J.C., 1997. Vertical accretion and shallow subsidence in a mangrove

572   forest of southwestern Florida, U.S.A. Mangroves and Salt Marshes 1, 173-186.

573 Cahoon, D.R., Hensel, P.F., Spencer, T., Reed, D.J., McKee, K.L., Saintilan, N., 2006.

574   Coastal wetland vulnerability to relative sea-level rise: Wetland elevation trends and

575   process controls. Wetlands and Natural Resource Management 190, 271-292.

576 Carvalho, L.M.V., Jones, C., Liebmann, B., 2004. The South Atlantic convergence zone:

577   Intensity, form, persistence, and relationships with intraseasonal to interannual activity

578   and extreme rainfall. Journal of Climate 17, 88-108.

579 Cavalcanti, V.F., Andrade, A.C.S., Soares, M.L.G., 2007. Germination of *Avicennia*

580   *schaueriana* and *Laguncularia racemosa* from two physiographic types of mangrove

581   forest. Aquatic Botany 86 (3), 285-290.

582 Colinvaux, P., De Oliveira, P.E., Patiño, J.E.M., 1999. Amazon Pollen Manual and Atlas.

583   Harwood Acad. Publi. Dordrecht, 332.

584 Cohen, M.C.L., Lara, R.J., 2003. Temporal changes of mangrove vegetation boundaries

585   in Amazônia: application of GIS and remote sensing techniques. Wetlan. Ecol. and

586   Manag. 11, 223-231.

587 Cohen, M.C.L., Souza Filho, P.W., Lara, R.L., Behling, H. Angulo, R., 2005. A model of

588   Holocene mangrove development and relative sea-level changes on the Bragança

589   Peninsula (northern Brazil). Wetlan. Ecol. and Manag. 13, 433-443.

590 Cohen, M.C.L., Behling, H., Lara, R.J., Smith, C.B., Matos, H.R.S., Vedel, V., 2009.

591   Impact of sea-level and climatic changes on the Amazon coastal wetlands during the

592   Late Holocene. Veg. Hist.and Archaeob., 10-20.

593   Cohen, M. C. L., Pessenda, L.C.R., Behling, H., Rossetti, D.F., França, M.C., Guimarães,

594   J.T.F., Friaes, Y.S., Smith, C.B., 2012. Holocene palaeoenvironmental history of the

595   Amazonian mangrove belt. Quat. Scn. Rev., 55, 50-58.

596   Cohen, M.L., Alves, I.C.C., França, M.C., Pessenda, L.C.R., Rossetti, D.F., 2015.

597   Relative sea-level and climatic changes in the Amazon littoral during the last 500

598   years. Catena 133, 441-451.

599   Cohen, M.C.L., Figueiredo, B.L., Oliveira, N. N., Fontes, N. A., França, M. C, Pessenda,

600   L. C.R., Souza, A. V., Macario, K., Giannini, P. C.F., Bendassolli, J. A., Lima, P.,

601   2020 . Impacts of Holocene and modern sea-level changes on estuarine mangroves

602   from northeastern Brazil. Ear. Surf. Proces. and Landfor. 45, 375-392.

603   Deines, P.,1980. The isotopic composition of reduced organic carbon. In Handbook of

604   Env. Isto. Geoche., 1. The Terrestrial Environment. (eds. P. Fritz and J. Ch. Fontes),

605   329-406. Elsevier.

606   Dominguez, J.M., Bittencourt, A.C.S.P., Martin, L., 1981. Esquema evolutivo da

607   sedimentação Quaternária nas feições deltaicas dos Rios São Francisco (SE/AL),

608   Jequitinhonha (BA), Doce (ES) e Paraíba do Sul (RJ). São Paulo. Rev. Brasil. de

609   Geociên. 11(4), 227-237.

610   Dominguez, J. L., Bittencourt, A. C. D. S. P., & Martin, L., 1992. Controls on Quaternary

611   coastal evolution of the east-northeastern coast of Brazil: roles of sea-level history,

612   trade winds and climate. Sedim. Geol. 80 (3-4), 213-232.

613   Dominguez, J.M.L., 2009. The Coastal Zone of Brazil, in: Dillenburg, S. R., Hesp, P. A.

614   (Eds.), Geology and geomorphology of Holocene Coastal Barriers of Brazil. Springer

615   Verlag, Berlin, 17–51.

616   Faegri, K., Inversen, J., 1989. Texbook of Pollen analysis. New York: John Wiley, 486.

617   Fellerhoff, C., Voss, M.,Wantzen, K.M., 2003. Stable carbon and nitrogen isotope

618   signatures of decomposing tropical macrophytes. Aquat. Ecol. 37, 361-375.

619   Fernandes, G.W., Goulart, F.F., Ranieri, B.D., Coelho, M.S., Dales, K., Boesche,

620   N., Bustamante, M., Carvalho, F.A., Carvalho, D.C., Dirzo, R., 2016. Deep into the

621   mud: Ecological and socio-economic impacts of the dam breach in Mariana,

622   Brazil. Nat Conservação 14(2), 35-45.

623   Fontes, N. A., Moraes, C. A., Cohen, M.C.L., Alves, I.C.C., França, M.C., Pessenda,

624   L.C.R., Francisquini, M., Bendassolli, J. A., Macario, K., Mayle, F., 2017. The Impacts

625   of the Middle Holocene High Sea-Level Stand and Climatic Changes on Mangroves

626   of the Jucuruçu River, Southern Bahia - Northeastern Brazil. Radiocar. 59, 215-230.

627   França, M.C., Francisquini, M.I., Marcelo, C.L.C., Pessenda, L.C.R., Rosseti, D.F.,

628   Guimaraes, J.T.F., Smith, C.B., 2012. The last mangroves in Marajó Island – Eastern

629   Amazon: Climate and/or Relative Sea-Level Changes Impacts. Rev. of Palaeobot.

630   Palynol. 187, 50-68.

631   França, M.C., Cohen, M.C.L., Pessenda, L.C.R., Rosseti, D.F., Lorente, F. L., Buso, A.,

632   Guimarães, J.T.F., Friaes, Y., 2013. Mangrove vegetation changes on Holocene

633   terraces of the Doce River, southeastern Brazil. Catena (Cremlingen), v. 110, p. 59-

634   69.

635   França, M.C., Francisquini, M.I., Cohen, M.C.L., Pessenda, L.C.R., 2014. Inter-proxy

636   evidence for the development of the Amazonian mangroves during the Holocene. Veg.

637   Hist. and Archaeobo. 23, 527-542.

638   França, M.C., Alves, I.C.C., Castro, D.F., Cohen, M.C.L., Rossetti, D.F., Pessenda,

639   L.C.R., Lorente, F.L., Fontes, N.A., Buso Jr., A.A., Giannini, P.C.F., Francisquini,

640   M.I. da., 2015. Multi-proxy evidence for the transition from estuarine mangroves to

641   deltaic freshwater marshes, Southeastern Brazil, due to climatic and sea-level changes

642   during the Late Holocene. Catena 155-166.

643   França, M.C., Alves, I.C.C., Cohen, M.C.L., Rossetti. D.F., Pessenda,L.C.R., Giannini,

644   P.C.F., Lorente, F.L., Buso Jr., A.A., Bendassolli, J.A., 2016. Millennial to secular

645   time-scale impacts of climate and sea-levelchanges on mangroves from the Doce River

646   Delta, Southeastern Brazil. Holocene 26, 1733-1749.

647   French, J.R., Stoddart, D.R., 1992. Hydrodynamics of salt marsh creek systems:

648   Implications for marsh morphological development and material exchange. Earth surf.

649   Proc.and landfor. 17 (3), 235-252.

650   Furukawa, K., Wolanski, E., 1996. Sedimentation in mangrove forests. Mang. and salt

651   mars. 1(1), 3-10.

652   Gil-Torres, W., Ulloa-Delgado, G., 2001. Caracterización, diagnóstico de los manglares

653   del departamento de Córdoba Corporación Autónoma Regional de los Valles del Sinú

654   y el San Jorge Montería, 195.

655   Gu, X., Feng, H., Tang, T., Tam, N.F.Y., Pan, H., Zhu, Q., Dong, Y., Fazlioglu, F., Chen,

656   L., 2019. Predicting the invasive potential of a non-native mangrove reforested plant

657   (Laguncularia racemosa) in China. Ecol. Engine. 139, 105591.

658   Guimarães, J.T.F., Cohen, M.C.L., Pessenda, L.C.R., França, M.C., Smith, C.B.,

659   Nogueira, A.C.R., 2012. Mid- and Late-Holocene sedimentary process and

660   palaeovegetation changes near the mouth of the Amazon River. Holocene 22, 359-370.

661   Grimm E.C., 1987. CONISS: A Fortran 77 program for stratigraphically constrained

662   cluster analysis by the method of incremental sum of squares. Computers &

663   Geoscience 13, 13-35.

664   Grimm, E.C., 1990. TILIA and TILIAGRAPH: PC spreadsheet and graphic software for

665   pollen data. INQUA Subcommission on Data-Handling Methods. Newsletter 4, 5-7.

666   Harper, C.W., 1984. Improved methods of facies sequence analysis. In: Walker, R.G.

667   (Ed.), Facies Models, 2nd ed. Geological Association of Canada, Ontario, Canada, pp.

668   11-13.

669   Hogarth, P.J., 2007. The Biology of Mangroves Oxford University Press, New York,

670   228p.

671   Hoguin, R., Restifo, F., 2012. Middle Holocene archaeology: dynamics of environmental

672   and socio-cultural change in South America. Quat. Int. 256, 1–87.

673   Hutchings, P., Saenger, P., 1987. The Ecology of Mangroves. Queensland: University of

674   Queensland Press.

675   Job, T., Penny, D., Morgan, B., Hua, Q., Gadd, P., Zawadzki, A., 2021. Multi-stage

676   Holocene evolution of the River Murray Estuary, South Australia. Holocene 31 (1),

677   50-65.

678   Kathiresan, K., Thangam, T. S., 1990. A note on the effects of salinity and pH on growth

679   of Rhizophora seedlings. Indian Forester 116 (3), 243-244.

680   Kirwan, M.L. and Murray, A.B., 2007. A coupled geomorphic and ecological model of

681   tidal marsh evolution. PNAS 104 (15), 6118-6122.

682   Krauss, K.W., McKee, K.L., Lovelock, C.E., Cahoon, D.R., Saintilan, N., Reef, R., Chen,

683   L., 2013. How mangrove forests adjust to rising sea level. New Phytologist 202, 19-

684   34.

685   Lamb, A.L, Wilson, G.P, Leng, M.J., 2006. A review of coastal palaeoclimate and relative

686   sea level reconstructions using $\delta13C$ and C/N ratios in organic material. Earth-Science

687   Rev. 75 (1), 29-57.

688   Lara, R.J., Cohen, M.C.L., 2009. Palaeolimnological studies and ancient maps confirm

689   secular climate fluctuations in Amazonia. Clim. Change 94, 399-408.

690   Lorente, F.L., Pessenda, L.C.R., Oboh-Ikuenobe, F., Buso Junior, A.A., Cohen, M.C.L.,

691   Meyer, K.E.B., Giannini, P.C.F., Oliveira, P.E., Rossetti, D.F., Borotti Filho, M.,

692   França, M.C., Castro, D.F., Bendassolli, J.A., Macario, K., 2014. Palynofacies and

693   stable C and N isotopes of Holocene sediments from Lake Macuco (Linhares, Espírito

694   Santo, southeastern Brazil): Depositional settings and palaeoenvironmental evolution.

695   Palaeogeography, Palaeoclimatology, Palaeoecology 415, 69-82.

696   Markgraf, V., D'Antoni H.L., 1978. Pollen Flora of Argentina. University of Arizona

697   Press: Tucson, AZ. Masselink, G., Gehrels, R., 2015. Coastal Environments & Global

698   Change. Copyright © 2014 John Wiley & Sons, Ltd.

699   Martin, L., Bittencourt, A.C.S.P., Vilas Boas, G.S., Flexor, J.M., 1980. Mapa geológico

700   do quaternário costeiro do estado da Bahia – 1:250.000: texto explicativo. Salvador:

701   Secretaria das Minas e Energia/coordenação da produção mineral.

702   Martin, L., Suguio, K., 1992. Variation of coastal dynamics during the last 7000 years

703   recorded in beach-ridge plains associated with river mouths: example from the central

704   Brazilian coast. Palaeogeog. Palaeoclimatol. Palaeoecol. 99, 119-140.

705   Martin L., Suguio K., Flexor J.M., Dominguez J.M.L., Bittencourt A.C.S.P., 1996.

706   Quaternary sea-level history and variation in dynamics along the central Brazil Coast:

707   consequences on coastal plain construction. Anais da Academia Brasileira de Ciências

708   68, 303-354.

709   Martin, L., Dominguez J.M.L & Bittencourt, A.C.S.P., 1998. Climatic control of coastal

710   erosion during a sea-level fall episode. An. Acad. Bras. Ci. 70: 249-266.

711 Martin, L., Dominguez, J.M.L., Bittencourt, A.C.S.P., 2003. Fluctuating Holocene

712   sealevels in eastern and southeastern Brazil: evidence from multiple fossil and

713   geometric indicators. Journal of Coastal Research, Royal Palm Beach 19, 101-124.

714 Masselink, G., Gehrels, R., 2015. Coastal Environments & Global Change. Copyright ©

715   2014 John Wiley & Sons, Ltd.

716 McKee, K.L., Cahoon, D.R., Feller, I.C., 2007. Caribbean mangroves adjust to rising sea

717   level through biotic controls on change in soil elevation. Global Ecology and

718   Biogeography 16 (5), 545-556.

719 Meyers, P.A., 2003. Applications of organic geochemistry to paleolimnological

720   reconstructions: a summary of examples from the Laurentian Great Lakes. Organic

721   Geochemistry 34, 261-289.

722 Miall, A.D., 1978. Facies types and vertical profile models in braided river deposits: a

723   summary. In: Miall, A. D. (Ed.) Fluvial Sedimentology. Calgary: Canad. Soci. of

724   Petrol. Geol., 597-604.

725 Milne, G.A., Bassett, E., 2005. Modeling Holocene relative sea-level observations from

726   the caribbean and South America. Quaternary Science Reviews 24 (10-11), 1183-

727   1202.

728 Monacci, N.M., Meier-Gruenhagen, U., Finney, B.P., Behling, H., Wooller, M.J., 2009.

729   Mangrove ecosystem changes during the Holocene at Spanish Lookout Cay, Belize.

730   Palaeogeog., Palaeoclimatol., Palaeoecol. 280, 37-46.

731 Munsell Color, 2009. Munsell Soil Color Charts, New Revised Edition. Macbeth Division

732   of Kollmorgen Instruments, New Windsor, NY.

733   Naidoo, G., Hiralal, O., Naidoo, Y., 2011. Hypersalinity effects on leaf ultrastructure and

734   physiology in the mangrove Avicennia marina. Flora-Morphology, Distribution,

735   Functional Ecology of Plants 206 (9), 814-820.

736   Peixoto, A.L., Rosa, M.M.T., Joels, L.C.M., 1995. Diagramas de Perfil e de Cobertura de

737   um Trecho da Floresta de Tabuleiro na Reserva Florestal de Linhares (Espírito Santo,

738   Brasil). Acta Botânica Brasilica 9 (2), 177-190.

739   Peixoto, A.L., Gentry, A., 1990. Diversidade e composição florística da mata de tabuleiro

740   na Reserva Florestal de Linhares (Espírito Santo, Brasil). Revista Brasileira de

741   Botanica 13, 19-25.

742   Pessenda, L.C.R., Ribeiro, A. de S., Gouveia, S.E.M., Aravena, R, Boulet, R, Bendassolil

743   J.A., 2004. Vegetation dynamics during the late Pleistocene in the Barreirinhas

744   regions, Maranhão State, northeastan Brazil, based on carbon isotopes in soil organic

745   matter. Quatern. Reser. 62, 183-193.

746   Pessenda, L.C.R., Gouveia, S.E.M., Ledru, M., Aravena, R., Ricardi-Branco, F.S.,

747   Bendassolli, J.A., Ribeiro, Adauto, de S., Saia, S.E.M.G., Sifeddine, A., Menor, E. de

748   A., Oliveira, S.M.B. de, Cordeiro, R.C., Freitas, A.M. de M., Boulet, R., Filizola, H.

749   F., 2008 . Interdisciplinary paleovegetation study in the Fernando de Noronha Island

750   (Pernambuco State), northeastern Brazil. Anais da Academia Brasileira de Ciências

751   (Impresso) 80, 677-691.

752   Pessenda L.C.R, Vidotto, E., De Oliveira P.E., Buso Jr, A.A., Cohen, M.C.L., Rossetti,

753   D. de F., Ricardi-Branco, F., Bendassol, J.A., 2012. Late Quaternary vegetation and

754   coastal environmental changes at Ilha do Cardoso mangrove, southeastem Brazil

755   Palaeogeog., Palaeoclimatol., Palaeoecol. 363-364, 57-68.

756 Peterson, B.J., Howarth, R.W., 1987. Sulfur, carbon, and nitrogen isotopes used to trace

757   organic matter flow in the salt-marsh estuary of Sapelo Island, Georgia. Limnol.

758   Oceanogr. 32, 1195-1213.

759 Reineck H.E., Singh L.E., 1980. Depositional Sedimentary Environments. Berlin:

760   Springer-Verlag, 551.

761 Reimer P.J., Bard E., Bayliss A., Beck J.W., Blackwell P.G., Bronk Ramsey C., 2013.

762   Reimer, P. J. (Ed.) IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–

763   50,000 Years cal BP. Radiocarbon 55 (4),1869-1887.

764 Roubik, D.W., Moreno, J.E., 1991. Pollen and spores of Barro Colorado. St. Louis:

765   Missouri Botanical Garden, 270.

766 Rossetti, D.F., Ricardi-Branco F., Bendassolli J.A., 2012. Late Quaternary vegetation and

767   coastal environmental changes at Ilha do Cardoso mangrove, southeastern Brazil.

768   Palaeogeog., Palaeoclimatol., Palaeoecol. 363, 57-68.

769 Rossetti, D.F., Bezerra, F.H., Dominguez, J.M.L., 2013. Late Oligocene-Miocene

770   transgressions along the equatorial and eastern margins of Brazil. Earth Science

771   Reviews 123, 87-112.

772 Salgado-Labouriau, M.L., 1973. Contribuição à palinologia dos cerrados. Rio de Janeiro:

773   Academia Brasileira de Ciências, 273.

774 Smith C.B., Cohen M.C.L., Pessenda L.C.R., França M.C., Guimarães J. T. F., Rossetti

775   D.de F., Lara R. J., 2011. Holocene coastal vegetation changes at the mouth of the

776   Amazon River. Review of Palaeobotany and Palynology 168, 21-30.

777 Snedaker, S.C., 1982. Mangrove species zonation: why? In: Sen, D.N. & Rajpurohit, K.S.

778   (eds.). Contributions to the ecology of halophytes: Tasks for vegetation science,vol. 2.

779   Springer, Netherlands, 111-125.

780 Sobrado, M.A., 2000. Relation of water transport to leaf gas exchange properties in three

781   mangrove species. Trees 14, 258-262.

782 Stuiver, M., Reimer, P.J., and Reimer, R.W., 2018. CALIB 7.1 [WWW program] at

783   http://calib.org, accessed 2019-5-27.

784 Suárez, N., Medina, E., 2005. Salinity effect on plant growth and leaf demography of the

785   mangrove, Avicennia germinans L. Trees 19, 721-727.

786 Suguio, K., Martin, L. e Flexor, J.M., 1980. Sea-level fluctuations during the past 6,000

787   years along the coast of the State of Silo Paulo, Brazil. In: N.A. Morncr (ed.), Earth

788   Rheology, Isostasy and Eustasy, John Willey and Sons, 471-486.

789 Suguio, K., Martin, L., Dominguez, J.M.L., 1982. Evolução da planície costeira de Rio

790   Doce (ES) durante o Quaternário: influência das flutuações do nível do mar. In:

791   Simpósio Do Quaternário Do Brasil, 4., 1982, Rio de Janeiro. Anais, Rio de Janeiro,

792   93-116.

793 Sukigara, C., Saino T., 2005. Temporal variations of $\delta^{13}C$ and $\delta^{15}N$ in organic particles

794   collected by a sediment trap at timeseries station off the Tokyo Bay. Continental Shelf

795   Research 25, 1749-1767.

796 Thom, B.G., 1984. Coastal landforms and geomorphic processes. In: Snedaker, S.C.,

797   Snedaker, J.C. (Eds.), The mangrove ecosystems: research methods. UNESCO,

798   Bungay, UK, 3-17.

799 Thomas R.G., Smith D.G., Wood J.M., Visser J., Calverley-Range E.A., Koster E.H.,

800   1987. Inclined heterolithic stratification-terminology, description, interpretation

801   andsignificance. Sedimentary Geology 53, 123-179.

802 Tognella, M.M.P, Cunha, S.R. da, Soares, M.L.G., Schaeffer-Novelli, Y., Lugli, D.O.,

803   2006. Mangrove Evaluation - An Essay. Journal of Coastal Research 39, 1219-1224.

804 Toniolo, T de F., Giannini, P.C.F., Angulo, R.J., de Souza, M.C., Pessenda, L.C.R., &

805   Spotorno-Oliveira, P., 2020. Sea-level fall and coastal water cooling during the Late

806   Holocene in Southeastern Brazil based on vermetid bioconstructions. Marine Geology,

807   106281.

808 Tomlinson P.B., 1986. The Botany of Mangroves. Cambridge University Press, USA.

809   413.

810 USEPA, 1999. Innovative Technology Verification Report: Sediment Sampling

811   Technology, Aquatic Research Instruments Russian Peat Borer, EPA/600/R-01/010.

812   Office of Research and Development.

813 Walker, M.J.C., Berkelhammer, M., Björck, S., Cwynar, L.C., Fisher, D.A., Long, A.J.,

814   Lowe, J.J., Newnham, R.M., Rasmussen, S.O., Weiss, H., 2012. Formal subdivision

815   of the Holocene Series/Epoch: a Discussion Paper by a Working Group of INTIMATE

816   (Integration of ice-core, marine and terrestrial records) and the Subcommission on

817   Quaternary Stratigraphy (International Commission on Stratigraphy). J. Quat. Sci. 27,

818   649–659.

819 Walker, R.G. & James, N.P., 1992. Facies models and modern stratigrahic concepts. In:

820   Walker R.G., James N.P. (Eds.). Facies models - response to sea level change. Ontario,

821   Canada: Geological Association of Canada, 1-14.

822 Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. Journal of

823   Geology 30, 377-392.

824 Wilson, G.P., Lamb, A.L., Leng, M.J., Gonzalez, S. Huddart, D., 2005. Variability of

825   organic $\delta 13C$ and C/N in the Mersey Estuary, U.K. and its implications for sea-level

826   reconstruction studies, Coastal and Shelf Science, London 64 (4) 685-698.

827 Woodroffe, C.D., 1982. Geomorphology and Development of Mangrove Swamps, Grand

828   Cayman Island, West Indies. Bulletin Marine Science 32 (2), 381-398.

829 Woodroffe, C., 1992. Mangrove sediments and geomolphology. In: Robertson & Alongi

830   (Eds) Tropical Mangrove Ecosystems. AGU, Washington, 7-41.

831 Woodroffe, C., 2002. Coasts: form, process, and evolution. Cambridge University Press,

832   New York.

833 Wolanski E., Mazda Y., King, B., Gay S., 1990. Dynamics, flushing and trapping in

834 Hinchinbrook channel, a giant mangrove swamp, Australia. Estuarine Coast. Shelf Sci.

835 31(5), 555-579.

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838 **FIGURES/TABLES CAPTIONS**

839 **Fig. 1.** Study area: a) Barreiras Formation, and Pleistocene and Holocene deposits under

840 the influence of the Doce River Delta; b) topographic profile showing the differences

841 between the topographic elevations of the Quaternary deposits, Barreiras Group, and

842 crystalline basement; c) LI-34 core location showing geomorphological features such as

843 beach ridges, herbaceous plain, and mangrove vegetation developed in the Holocene

844 (Google Earth); d) MBN core location, showing herbaceous plain and mangroves

845 developed in the Holocene (Google Earth); e) the contact between mangrove and

846 herbaceous vegetation in the São Mateus River mouth; f) the contact between mangrove

847 and herbaceous vegetation in the Barra Seca River mouth; g) mangrove vegetation

848 composed mainly by *Rhizophora* and *Laguncularia* in the MBN area.

849 **Fig. 2.** Summary of the MBN sediment core, showing sedimentary features, ^{14}C dating,

850 pollen data, and geochemical results.

851 **Fig. 3.** Summary of the LI-34 sediment core, showing sedimentary features, ^{14}C dating,

852 pollen data, and geochemical results.

853 **Fig. 4.** Pollen diagram record for core MBN. Ecological group abundance is shown in

854 percentage of total pollen sum. Phase boundaries are marked by the red dotted lines.

855 **Fig. 5.** Pollen diagram record for core LI-34. Ecological group abundance is shown in

856 percentage of total pollen sum. Zone boundaries are marked by black dotted lines.

857 **Fig. 6.** Model of paleoenvironmental changes in the late Holocene. Sea level fall was

858 expressed in the figure according to previous studies (Martin et al., 1980; Milne and

859 Bassett, 2005; Angulo et al., 2006).

860 **Fig. 7.** Diagrams for core MBN (a) and core LI-34 (b) illustrating the relationship between

861 δ^{13}C vs. C:N for the different coastal organic matter sources during the late Holocene in

862 southeastern Brazil. Interpretation is according to data presented by Meyers (2003) and

863 Lamb et al. (2006).

864

865 **Table 1.** Data on sediment samples selected for ^{14}C dating and results from cores MBN

866 and LI-34 (Doce River Delta) with cody site, laboratory number, depth, material, ages

867 ^{14}C yr BP conventional, calibrated, and median (using Calib 7.1; Stuiver, et al., 2018).

868 **Table 2.** Species from the Doce River Delta and their δ^{13}C value.

869