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1 **Title: When archives are missing, deciphering the effects of public policies**
2 **and climate variability on the Brazilian semi-arid region using sediment**
3 **core studies**

4
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25

26 **Abstract**

27 The northeastern region of Brazil is the most densely populated and biodiverse semi-arid
28 regions of the planet. Effects of the natural climate variability and colonization on the
29 landscape have been described since the beginning of the 16th century but little is known
30 about their effects on natural resources. Climate projections predict temperatures above 40 °C
31 and an increase in the number and duration of droughts at the end of the 21st century with
32 strong societal impacts. Here, we analyze the influence of public policies, human activities
33 and natural climate variability on the environment over the last 60 years. Our study is based
34 on sedimentological and environmental reconstructions from two sediment cores collected in
35 two dam lakes on the river Acaraú in the State of Ceará. Multiproxy analyses of both cores
36 (inorganic geochemistry, pollen, charcoal, remote sensing) at an annual resolution showed
37 that 1) at interannual scale composition and distribution of the dry forest (known as Caatinga)
38 were not affected by the alternance of drought and high moisture episodes; 2) at decadal scale
39 human activities such as agriculture were reflected by changes in vegetation cover and fishery
40 by progressive changes in lake trophic status; 3) public policies were able to promote changes
41 in the landscape e.g., land colonization with the regression of the dry forest and irrigation plan
42 able to amplify the deforestation and change the floristic composition. Thanks to paleo-
43 science approach, our environmental diagnosis should help future decision-making and
44 provide guidelines for preservation of resources and wellbeing of the inhabitants.

45

46

47 **Keywords**

48 Caatinga, lake reservoir, sediment, drought, land degradation, human impact

49

50

51 **1. Introduction**

52 The Brazilian semi-arid (BSA) is the world's most densely populated semi-arid region with
53 more than 54 million inhabitants. It also hosts 1 500 plant, 178 mammal, 591 bird, 177 reptile,
54 79 amphibian, 241 fish and 221 bee species (Ministerio do Meio Ambiente, 2007) that mostly
55 live in the dry deciduous forest biome known as *Caatinga*. The combination of rainfall
56 variability and intensive land use will make this region one of the world's most vulnerable to
57 climate change in the coming century (IPCC Climate Change *Synthesis Report*, 2014). The
58 rainfall regime has been highly variable since the 16th century with successive periods of high
59 precipitation and droughts. For example, 48 drought episodes have been reported of which 19
60 lasted two years or more, and in 1958, millions of people were obliged to flee starvation
61 (Marengo and Bernasconi, 2015). Climate variability, deforestation, the creation of
62 pastureland, irrigation, extensive farming activities, mining since the 17th century (Neto,
63 2012) and, more recently, overpopulation, have encouraged desertification (Centro de Gestão
64 e Estudos Estratégicos, 2016). Brazilian policies in the 20th century attempted to halt this
65 process through several land use initiatives and recovery of degraded areas (Centro de Gestão
66 e Estudos Estratégicos, 2017) although such projects were often limited to a single region, one
67 such example being « The Caatinga protected areas program » (Portuguese acronym UCCA)
68 developed by the Environmental Municipal Agency for a single municipality. About 447
69 reservoirs were built with a total capacity of 30 261 hm³ although today they only function at
70 18% of their capacity (<https://olhonagua.insa.gov.br>).

71 Since the beginning of the 21st century, in addition to natural variability and anthropogenic
72 land use change, ongoing climate change is again challenging the BSA. Both global and
73 regional climate change scenarios suggest rainfall deficits and increased aridity will prevail in
74 the region by the second half of the 21st century (Marengo and Bernasconi, 2015). Aware of
75 these risks, the Brazilian government set up the “Recovery of degraded areas and reduction of

76 climate vulnerability” (Portuguese acronym URAD) initiative to address the control of the
77 main drivers of land degradation in the Caatinga biome.

78 Land cover is a common proxy for the long-term impacts of climate change and land use
79 (Lebel et al., 2018). For an integrated assessment of the driving forces likely to affect the
80 landscape, data are collected in field surveys (Ferrenberg et al., 2015), from agricultural
81 yields, and from aerial photographs (Barbosa and Kumar, 2016), as the latter provide an
82 accurate view of the effects of forcing on a landscape and can distinguish anthropogenic from
83 natural forcing in one or several specific time windows (IPCC, 2018). However, in the BSA,
84 the scarcity and the irregularity of such data make it impossible to analyze these effects on the
85 landscape, thereby preventing the production of the crucial information required to take
86 sustainable resource management decisions. Moreover, field surveys do not allow continuous
87 long-term observations (at the scale of several decades) that would be necessary to account
88 for the impacts of current and future climate change when evaluating the future ecosystem
89 services provided by this semi-arid biome. When such archives are absent, sediment cores
90 from lakes (e.g. Levine et al 2012) or reservoirs (Cardoso -Silva et al 2016) are commonly
91 used to reconstruct the chronology of pesticides (Sabatier et al 2014), organic pollutants
92 (Zhang et al 2019), trophic history (Levine et al 2012) to estimate degradation and propose
93 some alternatives. However these studies do not inform about total landscape and
94 environmental histories. Here to evaluate the combined effects of public policies, human
95 activities and natural climate variability on the total environment and landscape we aim
96 testing a new approach based on multiproxy analyses geochemistry and biological proxies
97 crossed with the instrumental data and the launching of the main public policies and, evaluate
98 how well the sediment cores are able to reconstruct an integrated history of the landscape in
99 the BSA (Appendix A).

100 For our analysis, we proposed an approach based on indirect reconstructions and produced
101 continuous data from archives retrieved from reservoir sediments, using paleo-limnological
102 techniques. Multiproxy analyses (sedimentological, geochemical, pollen, charcoal) associated
103 with a chronology based on short-lived radionuclides were performed to characterize the
104 signature of both climate variability and land use in the landscape continuously over time.
105 The aim of the paper is twofold. Firstly, to test a new approach for historical reconstruction of
106 a landscape in the absence of archives. Secondly, to provide reliable data to understand the
107 changes in landscape resources in recent decades in order to enable policy makers to
108 incorporate these factors to insure the sustainable development of the region.

109

110 **2. Study area**

111 **1.1 Acaraú-Mirim and Araras dams**

112 Our study focused on two dam reservoirs, Acaraú-Mirim and Araras, located in the
113 hydrographic basin of Acaraú, which covers 10% of the total surface area of the State of
114 Ceará with 15 dams along the Acaraú River alone (Fig. 1). The Acaraú River is 320 km long,
115 its headwaters are in the Serra da Mata (700 m asl) near the city of Monsenhor Tabosa and the
116 river flows into the Atlantic Ocean. The Acaraú-Mirim reservoir (03°30.268'S; 40°16.766'W)
117 (ACA) is located in the district of Ipaguaçu, 84 m asl, at the foot of the Serra de Meruoca that
118 feeds the dam; the dam spillway feeds the Acaraú River just below the dam. The montane is
119 covered with a dense seasonal deciduous (Caatinga) and semi-deciduous forest. Annual
120 precipitation at Meruoca (990 m asl) is 1 400 mm. The dam has a capacity of 52 000 000 hm³
121 and is used to supply the city of Massapê and farms in the vicinity with water for irrigation
122 and fishery activities (Gurgel and Fernando, 1994). The Araras reservoir (04°12.559'S;
123 40°27.254'W) (ARA) (183 m asl) is located in the seasonal tropical deciduous forest
124 landscape in the district of Varjota and provides water for ~141,000 people. Mean annual

125 precipitation is 880 mm. The dam has a capacity of 891 000 000 hm³ and is intended to
126 supply drinkable water to three cities and their surroundings, as well as water for intensive
127 irrigation (Araras Norte Project), local irrigation and fishery. These reservoirs normally
128 capture a large volume of water during the rainy season, which is irregular in intensity and
129 duration because of the complex climatic pattern (Marengo and Bernasconi, 2015).

130

131 **1.2 Climate**

132 Between 1990 and 2010, mean annual rainfall in the Acaraú basin was 913 mm. For 45% of
133 the period, annual rainfall was above the mean and for 15% of the period, annual rainfall was
134 below the mean. Rainfall is concentrated between March and May. Thirteen drought events
135 have been recorded in the BSA region in the last 60 years: 1958, 1966, 1970, 1976, 1979–
136 1981, 1982–1983, 1992–1993, 1997–1998, 2001–2002, 2005, 2007, 2010, and 2012–2015
137 (Alexander et al., 2018; Marengo and Bernasconi, 2015). The February–May rainy season in
138 BSA in 2012 was the driest between 1961 and 2012, and the two driest years since 1961 were
139 1982 and 2012. During the dry/wet years, inter hemispheric gradient is steep and the ITCZ
140 stays in a northern/southern position while the SST of the equatorial Pacific is anomalously
141 warm/cold. Model predictions show a scenario with a warmer SST in the northern Atlantic,
142 less rainfall and warmer temperatures in the BSA.

143 The climate of the mountain area near ACA is moister than the inland climate at ARA due to
144 the relief and the proximity of the ocean. Consequently, differences in rainfall anomalies are
145 observed between our two sites. ACA with 1 400 mm rainfall per year is less sensitive to
146 drought than the whole hydrographic basin comprising Acaraú and ARA.

147 At ACA, the driest years were 1983, 1992-93, 1997-98, 2005 and 2012-2015. High moisture
148 rates were recorded in 1985, 1994 and 2009.

149 At ARA, monitoring started in 1987. The driest years recorded were 1992-93, 1997-98, 2012-
150 2015 and the wettest years were 1989, 1995 and 2009. Considering the Acaraú hydrographic
151 basin as a whole, the driest years were 1979-83, 1992-93, 1998, 2012-2016. Based on these
152 observations, the year 2005 was considered « dry » only at ACA, near the coast. Correlations
153 with the Pacific Decadal Oscillation (PDO 1900-2013) anomaly show that it was negative
154 during the driest years: 1992, 1997-2003, and 2011-2013, while no correlation was observed
155 with the AMO anomaly. A negative anomaly in tropical North Atlantic SST was observed in
156 1970-75, 1982-84, 1992-93 and in 1997-98 a sharp decrease was observed but the anomaly
157 remained positive. Another correlation between SST and rainfall is observed when
158 considering the SST gradients between tropical North and South Atlantic, the
159 interhemispheric SST dipole, with the driest /wettest years when the S/N Atlantic SST was
160 colder/warmer. Indeed, Northeastern Brazil is one of the key regions that are severely affected
161 by the meridional mode of tropical Atlantic SST variability (Alexander et al., 2018). During
162 at least the last 50 years, the changes in SST have been closely correlated with rainfall
163 variability.

164

165 **1.3 Vegetation**

166 The Caatinga dominium is one of the three arid and semi-arid cores of the South American
167 continent (Andrade-Lima, 1981). The Caatinga dominium is a mosaic of tropical thorn
168 woodland and very dry thorn forest at altitudes below 500-600 m asl and dry forest at higher
169 altitudes (*sensu* the Holdridge life zone ecology). The phytogeographic classification system
170 of Brazil is called savanna-stepic (IBGE, 2010) and represents the dryland biome in Brazil. It
171 is located in northeastern semi-arid region, which occupies 11% of the country with an area of
172 about 1.3 million km². Delimitation was based on rainfall, mean anual rainfall below 800 mm,
173 aridity index up to 0.5, and risk of drought > 60% relative to the 1970–90 climatology (Joly et

174 al., 1999). Despite the semi-arid physiognomy, the Caatinga hosts high biomass and high
175 biodiversity.
176 Four main types of tropical vegetation (Holdridge, 1967) are observed in the Acaraú River
177 Basin: very dry thorn forest (Caatinga) and three types of seasonal dry forests on the slopes
178 and tops of mountains (deciduous, semi-deciduous with babaçu and evergreen forest). The
179 dominant ecosystem is the very dry thorn forest or Caatinga associated with stony
180 impermeable *crystalline soils adapted to* hydric deficiency. At Acaraú, the Caatinga has been
181 severely impacted by human activities and hotspots of ongoing desertification.
182 Intensive cotton crops, introduction of grazing in the 16th century in the Acaraú Basin and
183 wood cutting have greatly modified the Caatinga. The degradation of the arboreal Caatinga
184 led to expansion of the shrubs and grasses observed today. The limiting factors for
185 agriculture, i.e. the climate, shallow soil, stony surface, hydric deficiency) obliged the
186 inhabitants to practice itinerant agriculture, in which the land is abandoned after 2 or 3 years,
187 leaving behind secondary vegetation of no economic value (Araújo Filho, 1997) (Appendix
188 D).

189

190 **1.4 Ecological indicators**

191 The following species were assigned to the drought tolerant group *Mimosa caesalpinifolia*, *M*
192 *teniflora*, *Piptadenia stipulacea*, *Anadenanthera colubrina*, *Poincianella bracteosa*,
193 *Combretum*, *Myracrodruon urundeuva*, *Spondias*, *Zizyphus joazeiro*. *Mimosa caesalpinifolia*
194 is the dominant arboreal taxon in the ecosystem despite being very sensitive to degradation in
195 areas susceptible to desertification. These trees occur naturally in the Caatinga and are one of
196 the main sources of stakes for fences in Northeastern Brazil. Considering the climatic
197 conditions of the Brazilian semi-arid region, *Mimosa caesalpinifolia* is assumed to be a fast-
198 growing plant species, and is the wood used as fuelwood and for charcoal production

199 (Albuquerque *et al.*, 2009; Milliken *et al.*, 2018). *Combretum leprosum* is a good pollen
200 producer although not abundant in the vegetation. It grows easily in degraded areas.
201 *Alternanthera*, Poaceae, Cyperaceae, *Mitracarpus* and *Borreria* are common in the
202 herbaceous strata of the Caatinga, including on the margins of the reservoirs.

203

204 **2. Material and methods**

205

206 **2.1 Coring**

207 Two sediment cores were collected in two reservoirs, Acaraú Mirim (ACA) and Araras
208 (ARA) with a gravity corer UWITEC pushed into the sediment in a stable area of the
209 reservoir where the height of the water column was between 6 and 7 m, to guarantee
210 permanent water. The ACA 15-2 core went down to a depth of 97 cm. The ARA 15 core went
211 down to a depth of 60 cm. Cores were split in half using a cutter and a thin metal wire. One
212 half core was kept intact and sent to the EDYTEM laboratory in Chambéry, France for XRF
213 analyses the other half, used for proxy analyses, was cut into 1-cm thick sections, that were
214 immediately placed in plastic bags for storage and kept refrigerated in the laboratory until
215 processing and analysis. Proxy analyses were performed on alternate 1-cm samples.

216 The base of core ACA 15-2 is composed of compact organic sandy clay up to 80 cm, a layer
217 of fine dark clay between 80 and 77 cm, and fine brown organic clay to the top of the core.

218 The ARA 15 core is composed of fine organic clay with loose wet sediment in the top 10 cm.

219 To define an age depth relation for each core, 13 samples from ACA and 11 samples from
220 ARA were sent to *Laboratoire Souterrain de Modane* France for short-lived radionuclide
221 measurements.

222

223 **2.2 Dating**

224 ^{210}Pb , ^{226}Ra , and ^{137}Cs activities were determined using planar Broad-Energy Germanium
225 (BEGe) detectors placed at the *Laboratoire Souterrain de Modane* following (Reyss et al.,
226 1995) on 1- to 3-cm-thick samples with 12 samples on ARA15 sediment core and 10 samples
227 on ACA15 sediment core. The levels of ^{226}Ra activity were determined using its short-lived
228 daughters ^{210}Pb (295- and 352-keV peaks) and ^{214}Bi (609-keV peak), assuming secular
229 equilibrium with ^{226}Ra . ^{210}Pb (22.3 y), ^{241}Am (432.2 y), ^7Be (53.4 d), and ^{137}Cs (30.2 y) activity
230 levels were directly measured by their gamma emissions at 46.5, 60, 477, and 662 keV,
231 respectively. Excess ^{210}Pb activity was calculated by subtracting ^{226}Ra -supported activity from
232 total ^{210}Pb activity.

233

234 **2.3 Sedimentological and geochemical analyses**

235 The grain size distributions of core ACA15 were determined using a Malvern Mastersizer S
236 (EDYTEM lab) at a 1 cm continuous interval. After inserting the bulk sediment into the
237 granulometer, ultrasound was applied to minimize particle flocculation. Core ACA15 was
238 also sampled at 1-cm steps and dried at 60 °C during 4 d to obtain its dry bulk density, and
239 then the LOI of each sample was measured using the protocol of Goldberg (1963) and Heiri et
240 al. (2001). The LOI at 550 °C and 950 °C corresponds to the organic and carbonate
241 components of the sediment, respectively.

242 The relative concentrations of major elements were analyzed on the surface of the sediment
243 core by X-ray fluorescence (XRF) at high resolution (5 mm sampling step) with an Avaatech
244 Core Scanner (EDYTEM Laboratory, CNRS-University Savoie Mont Blanc). The X-ray
245 beam was generated with a rhodium anode and a 125- μm beryllium window, which allows a
246 voltage range of 7–50 kV and a current range of 0–2 mA. Element intensities were expressed
247 in counts per second (cps). Geochemical data were obtained with different settings depending
248 on the elements analyzed. They were adjusted to 10 kV and 1 mA for 20s to detect Si, Ca, Al,

249 Fe, Ti, K, Mn, and S. For heavier elements (i.e. Sr, Rb, Zr, Br, and Pb), measurements were
250 performed at 30 kV and 0.75 mA for 30 s (Jansen et al., 1998). Identification of relationships
251 between element depth-series, the data on each core was subjected to principal component
252 analyses (PCA) using vegan package (Oksanen et al., 2018) on the R platform (R Core Team,
253 2018).

254

255 **2.4 Pollen analyses**

256 Pollen analyses were performed at 1 cm intervals on 76 samples from ACA and 50 samples
257 fom ARA. *Lycopodium* spikes were used to estimate pollen concentrations (Stockmarr, 1971).
258 The samples treatment followed standard protocol (Faegri and Iversen, 1975; Kümmel and
259 Raup, 1965). A minimum of 300 terrestrial grains were counted per sample. Pollen grains and
260 spores were identified using the reference pollen collection of about 130 Caatinga taxa held at
261 the Prisco Bezerra Herbarium of the Federal University of Ceará, and several pollen atlases
262 (Miranda and Andrade, 1990; Oliveira and Santos, 2014; Radaeski et al., 2013; Salgado-
263 Labouriau, 1973; Silva et al., 2016; RCPol).

264

265 **2.5 Burning biomass**

266 The two cores (ACA 15 and ARA 15) were sampled continuously in each 1-cm layer for the
267 charcoal analyses and prepared using the following steps: (1) Samples were soaked in 5%
268 KOH solution; (2) particles were deflected and bleached in a 10% NaOCl solution; (3) 160-
269 µm mesh was used to separate microscopic coal particles; and (4) microcharcoals were
270 analyzed under a stereomicroscope and using the image analysis software WindSeedle
271 (Umbanhowar and Mcgrath, 1998).

272

273 **2.6 Sea Surface Temperature**

274 Sea surface temperature (SST) data were taken from the NOAA's Extended Reconstructed
275 Sea Surface Temperature, version 4 (ERSSTv4) dataset (Boyin et al., 2015.), available on 2° x
276 2° global grids, for the years 1950-2017. In order to examine the role of SST, we computed an
277 index of area-averaged SST anomalies within the northern Tropical Atlantic (1°–20° N, 48°-
278 20° W) for the December-February season. Anomalies are relative to the 1981-2010 monthly
279 average.

280

281 **2.7 Remote sensing**

282 We selected the LANDSAT images with the lowest cloud cover index between the years 1973
283 and 2016. The images were analyzed and interpreted using the functions available in a
284 Geographic Information System (GIS) software for vector editing, cartographic projection
285 conversion and digital image processing. All images were redesigned for the UTM projection,
286 SIRGAS 2000 datum, zone 24 of the southern hemisphere.

287

288 **3. Results**

289 **3.1 Age model**

290 A chronological framework was established using short-lived radionuclides measurements.
291 The ²¹⁰Pb excess profiles were plotted on a logarithmic scale (Fig. 2a) and we applied the
292 Constant Flux Constant Sedimentation model (CFCS) (Goldberg, 1963) for our age model.
293 For ACA 15 we obtained a mean accumulation rate of 13.8 +/- 2.25 mm.yr⁻¹ and the base of
294 lake sediment dated to 1963 +/- 8.5 yr AD. For ARA15, the ²¹⁰Pb excess profile (Fig. 2b)
295 showed a regular decrease interrupted by drops in ²¹⁰Pbex activity. Following Arnaud et al.
296 (2002), the low values of ²¹⁰Pbex were disregarded for the construction of the synthetic
297 sedimentary record, because the values are related to sedimentary facies that are considered to
298 be instantaneous deposits (Fig. 2b) illustrated by an increase in Si content, corresponding to

299 facies 2. Plotted on a logarithmic scale, the ^{210}Pb activity vs corrected depth revealed a
300 linear trend. Applying the CFCS model, we obtained a mean accumulation rate of 7.17 ± 1.45
301 $\text{mm}\cdot\text{yr}^{-1}$. Ages were then calculated using the CFCS model applied to the original
302 sediment sequence to provide a continuous age–depth relationship and an age interval of the
303 four instantaneous deposits corresponding to facies 2 (1980 ± 7 yr AD, 1976 ± 8 yr AD, 1972 ± 9
304 yr AD, 1964.5 ± 10.5 yr AD). The base of the lake sediment (facies 1 and 2) dated to 1959.5
305 ± 11.5 yr AD in good agreement with the dam construction in 1958 AD. Values for ^{137}Cs
306 activities were under the limit of detection in both cores.

307

308 **3.2 Depositional environment**

309 Color, grain size, loss on ignition (LOI), and sedimentary structure of the sediments in the
310 reservoir (Fig. 3, 4, 5) allowed to identify three different sedimentary facies in both cores. A
311 brown to green fine-grained sediment (facies 1) in the upper part of both cores (0-74.5 cm in
312 ACA15; and 0-45.5 cm in ARA15), a grey fine-grained sediment (facies 2) interbedded at
313 different depths in facies 1 and a brown coarse sediment (facies 3) at the base of each core
314 (95.5 - 74.5 cm in ACA15; 60 - 45.5 cm in ARA15). At ARA, the top 10 cm of the record was a
315 mixture of sediments/water interface and was considered as a single sample.

316 PCA variables and individual projections highlighted the correlation between different
317 elements in the two cores (Fig. 3). Dimensions 1 and 2 (hereafter Dim1 and Dim2) represent
318 71% and 78% of the total variance for ARA15 and ACA15, respectively (Fig. 4). In both
319 lakes, the ordination of variables among the first two axes are quite comparable and identify
320 the same main factors of variations, probably linked to the common geological context and
321 origin of the lakes. Three main chemical end-members or units were identified (Fig. 3). The
322 first one was positively correlated with Dim1 and yielded high positive loadings for major
323 terrigenous elements such as K, Zr, Sr and to a lesser extent Ca in both cores, plus Rb in

324 ARA15, and plus Si in ACA15. The second pole with negative loadings on Dim1 made it
325 possible to differentiate Br, S, Mn probably linked to in-lake processes: organic matter (Br)
326 and changes in oxic/anoxic conditions (Mn) in the lake system. The third end-member with a
327 positive loading on Dim2 included other terrigenous elements: Ti and Al in both cores, plus Si
328 and Pb in ARA15 and Rb in ACA15. We were able to separate the two terrigenous end-
329 members thanks to their grain size, the size corresponding to K, Zr, Sr was related to the sand
330 fraction of the sediment and the one enriched in Ti, Al was related to the fine-grained fraction
331 (< 4 μm) of the sediment. Fe was located between organic and the fine terrigenous end-
332 member, probably linked to its redox sensitive behavior. Adding the lithological facies 1, 2
333 and 3 allowed us to map the geochemical distribution of the data (Fig. 3, 7, 9). Mapping the
334 units in the PCA revealed a clear link between facies 1 and the second end-member related to
335 organic rich sediment (LOI_{550°C} around 15%) linked to long-term sedimentation in the lake
336 system (Fig. 5). Facies 2 was positively correlated with Dim2 and hence with the fine-grained
337 terrigenous end-member and probably with the high terrigenous input from the watershed due
338 to erosion during high rainfall events/periods. Facies 3 was positively correlated with Dim1
339 linked to the coarse sediment at the base of each sediment sequence, probably corresponding
340 to soil sediment that existed before the dam was constructed at each site.

341

342 **3.3 Reconstruction of the tree cover**

343 The composition of the vegetation was reconstructed from pollen analyses (Fig. 7, 8, 9, 10;
344 Appendix). Among the tree taxa of the Caatinga *Mimosa caesalpinifolia*, *M tenuiflora*,
345 *Piptadenia stipulaceae*, *Anadenanthera colubrina*, *Poincianella bracteosa*, *Combretum*
346 *leprosum*, *Myracrodruon urundeuva*, *Spondias* sp., *Zizyphus joazeiro* were assigned to the
347 drought tolerant group (Lima et al., 2018). *M caesalpinifolia*, one of the dominant arboreal
348 taxa in the Caatinga is very sensitive to degradation (Milliken et al. 2018). *C leprosum* is a

349 good pollen producer that grows easily although not abundantly in degraded areas (Milliken *et*
350 *al.*, 2018). *Alternanthera*, Poaceae, Cyperaceae, *Mitracarpus* and *Borreria* are common in the
351 herbaceous strata of the Caatinga (Costa *et al.*, 2017), including on the margins of the
352 reservoirs (Tabosa *et al.* 2012).

353 For ACA15, five pollen zones and 81 different pollen and spore types provide evidence for
354 several changes in the landscape during the last 55 years (Fig. 6, 7, Appendices B, C).

355 The basal pollen zone (ACA-I, 75 – 64.5 cm; 11 samples; 1961 to 1969 AD) comprises
356 taxa of the Caatinga with abundant arboreal pollen (27-48%). Fabaceae pollen, mainly
357 *Mimosa caesalpiniiifolia* (21-44%) and *Mimosa tenuiflora* (0.4-4%), was well represented.
358 Drought tolerant tree pollen taxa ranged from 1% to 6%. This group was represented by
359 *Mimosa tenuiflora*, *Piptadenia stipulacea*, *Anadenanthera colubrina*, *Poincianella*
360 *bracteosa*, *Combretum leprosum*, *Myracrodruon urundeuva*, *Spondias* and *Zizyphus*
361 *joazeiro* pollen grains. The herb taxa of the Caatinga were also well represented. A single
362 pollen grain of *Zea mays* was counted at a depth of 67 cm. Scattered pollen grains
363 belonging to taxa of the seasonal semi-deciduous forest - Serra da Meruoca - were
364 observed in this zone. Aquatic taxa ($\leq 2\%$) and fern spores ($< 2\%$) were scarce. The
365 number of carbonized particles was low and infrequent in this period.

366 Zone ACA-II (64.5 – 48.5 cm; 16 samples; 1969 to 1981 AD) was characterized by higher
367 values of tree pollen taxa (44-62%). Although *Mimosa caesalpiniiifolia* (31-51%) was the
368 most abundant taxon, greater numbers of *Mimosa tenuiflora* (2-10%), *Piptadenia stipulacea*
369 (0.3-3%) and *Senna* (0.3-3%) accounted for the increase in arboreal pollen. Drought tolerant
370 tree pollen taxa reached higher values (5-13%), mostly due to increased percentages of
371 *Mimosa tenuiflora* (2-10%) and *Piptadenia stipulacea* (0.3-3%) pollen. While pollen of
372 *Anadenanthera colubrina* appeared in more samples than previously, percentages of
373 *Combretum leprosum* pollen were still very low (0-1%). Pollen from *Alternanthera* (15-25%)

374 and Poaceae (4-15%) were still well represented, whereas pollen from *Borreria* (2-18%) and
375 *Mitracarpus* (1-4%) declined and both Asteraceae (0-2%) and Urticaceae (0-2%) pollen were
376 still only present at lower proportions. Abundances of Cyperaceae pollen remained stable (2-
377 5%) but both *Cleome* (0-4%) and the aquatic plant *Echinodorus* (0-2%) increased slightly in
378 this zone. The amount of charcoal particles was still low in this zone.

379 The pollen assemblages of the ACA-III zone (48.5 – 37.5 cm; 11 samples; 1981 to 1988 AD)
380 were characterized by a significant decrease (from 42% to 16%) in arboreal pollen. NAP taxa
381 of the Caatinga were well represented. Pollen of *Zea mays* (<1%) appeared more frequently.
382 There was a marked decrease in arboreal pollen, mostly due to the decline in *Mimosa*
383 *caesalpiniifolia* (7-34%). Drought tolerant tree pollen taxa decreased (1-8%), mainly due to
384 the low percentages of pollen of *Mimosa tenuiflora* (0.2-5%) and the low proportions of
385 *Piptadenia stipulacea* (0-2%) and *Myracrodruon urundeuva* (0-1%). However, while the
386 proportions of *Combretum leprosum* pollen remained low at the base of the zone (0.3%) they
387 increased to 3% toward the top. Dam bank taxa were more abundant (4-12%) than in zone
388 ACA-II, mainly due to higher proportions of Cyperaceae (1-8%) but also *Cleome* (2-4%)
389 pollen. Aquatic taxa (<2%) were slightly less frequent than in the previous zone. Charcoal
390 particles were very scarce in this period.

391 ACA-IV (37.5 – 25.5 cm; 12 samples; 1988 to 1998 AD) showed an increasing trend in
392 arboreal pollen abundances (30-61%), whereas the opposite was observed for non-arboreal
393 pollen percentages (35-63%). Arboreal pollen was continuously represented by *Mimosa*
394 *caesalpiniifolia* (26-54%) in which there was a marked increase compared to the previous
395 zone. Among non-arboreal pollen, there was a significant decrease in *Alternanthera* (12-
396 25%), *Mitracarpus* (0-5%), Asteraceae (<2%), Urticaceae (0-2%) and in *Acalypha* (0-2%).
397 Pollen of Poaceae (2-9%), *Zea mays* (<1%) and *Borreria* (4-23%) decreased toward the top of
398 the zone. The increase in the pollen curve for drought tolerant tree taxa (2-11%) was mainly

399 due to higher pollen counts of *Mimosa tenuiflora* (1-9%), but *Piptadenia stipulacea* (<2%),
400 *Combretum leprosum* (<2%) and *Myracrodruon urundeuva* (0-1%) remained low. Pollen of
401 *Poincianella bracteosa* appeared for the first time at 35 cm. Abundances of plant species
402 growing on the dam banks (2-8%) decreased in comparison to the previous zone. No charcoal
403 particles were counted in this zone.

404 The uppermost pollen zone (ACA-V, 25.5 - 0 cm; 26 samples; 1998 to 2015 AD) was
405 characterized by stable arboreal (37-63%) and non-arboreal (32-56%) pollen taxa. *Mimosa*
406 *caesalpiniifolia* (28-52%) dominated the arboreal pollen group, while *Alternanthera* (11-
407 21%), Poaceae (3-11%), *Borreria* (10-24%) and *Mitracarpus* (1-8%) accounted for the
408 highest values in the non-arboreal pollen group. Pollen of *Zea mays* (<2%) was still present.
409 Proportions of pollen of drought tolerant tree pollen taxa increased from 3% to 14%.
410 Abundances of *Mimosa tenuiflora* (1-11%) and *Myracrodruon urundeuva* (0-2%) pollen
411 remained stable, while percentages of *Combretum leprosum* pollen continued to increase (0.3-
412 4%). Pollen of *Piptadenia stipulacea* (0-2%), *Anadenanthera colubrina* (<1%) and *Senna* (0-
413 3%) pollen increased slightly. Pollen of Cyperaceae (2-10%) and *Cleome* (1-6%) reached
414 their highest values in the whole record. The percentage of moist semi-deciduous forest
415 increased to 2% due to higher proportions of pollen of *Cecropia* (<1%), Myrtaceae (<1%),
416 *Anacardium occidentale* (<1%) and *Attalea speciosa* (0-1%). Pollen of Sapindaceae (not
417 shown in the diagram) and *Copaifera* appeared for the first time in this zone. The number of
418 carbonized particles increased markedly in this period, but gradually decreased again toward
419 the top.

420 For ARA15, constrained cluster analysis divided the pollen diagrams into four main zones
421 (ARA-I to IV) and 74 pollen taxa and four spore types were identified (Fig. 8, 9; Appendices
422 B, C).

423 The top 10 cm of the record was a mixture of sediment/water interface and was considered as

424 a single sample. Based on the constrained cluster analysis as well as the 74 pollens and four
425 different spore types identified, the pollen diagrams were divided into four main zones (ARA-
426 I to IV).

427 Zone ARA-I (60 – 45.5 cm; 15 samples; before 1960 to 1966 AD) was characterized by high
428 percentages of NAP (62–84%) and low percentages of AP (9-31%). Pollen from drought
429 tolerant tree taxa ranged from 3% to 13%. This group was represented by *Mimosa tenuiflora*,
430 *Piptadenia stipulacea*, *Anadenanthera colubrina*, *Poincianella bracteosa*, *Combretum*,
431 *Myracrodruon urundeuva*, *Spondias* and *Zizyphus joazeiro* pollen grains. Low abundances of
432 AP were mostly due to lower percentages of *Mimosa caesalpinifolia* pollen (1-16%) and
433 *Mimosa tenuiflora* pollen (1-8%). Pollen of *Croton* reached higher values, between 1% and
434 7%. The NAP were dominated by pollen of *Alternanthera* (33-54%), Poaceae (5-12%),
435 *Borreria* (1-4%), *Mitracarpus* (4-10%), Asteraceae (4-16%) and other herbaceous plants
436 (*Froelichia/Gomphrena*, *Euphorbia* and *Microtea*) not shown on the diagram. Pollen grains
437 of the moist seasonal semi-deciduous forest occurred sporadically. This zone contained high
438 pollen abundances of sedges (Cyperaceae 7-20%) as well as herbs such as *Cleome* (0-2%) and
439 *Cuphea* (0-2%) that grow on the banks of the dam. The aquatic group was well represented by
440 pollen of *Echinodorus* (6-19%) and spores of *Salvinia* (0-2%). Carbonized particles were only
441 present in the uppermost part of the sample. The seasonal semi-deciduous forest group
442 increased up to 14% in this zone, because of higher proportions of Myrtaceae (0-11%) pollen.

443 Zone ARA-II (45.5 – 39.5 cm; five samples; 1966 to 1972 AD) was marked by an increase in
444 AP from 40% to 53%, mostly due to an increase in *Mimosa caesalpinifolia* with values up to
445 33%. The higher representation of pollen from drought tolerant tree pollen taxa, which varied
446 between 9% and 25%, was due to the high pollen frequencies of *Mimosa tenuiflora* (5-17%),
447 *Piptadenia stipulacea* (1-5%) and *Myracrodruon urundeuva* (0.3-3%) while *Combretum*
448 pollen frequencies remained stable (0.3-2%). Abundances of *Croton* (0-2%) pollen decreased

449 in this zone. Herbs, mostly represented by pollen of *Alternanthera* (5-21%), Poaceae (3-15%),
450 *Borreria* (1-2%), *Mitracarpus* (2-12%), Asteraceae (2-10%) and Urticaceae (1-2%) were less
451 frequent. The moist semi-deciduous forest taxa increased to 14% in this zone, because of
452 higher proportions of Myrtaceae (0-11%) pollen. The abundance of herbs growing on the dam
453 banks decreased (4–10%), due to less frequent Cyperaceae pollen (2-8%). The proportion of
454 aquatics (0.6–6%) was lower than in the previous zone due to the decline of *Echinodorus*
455 pollen (0.6-4%) and the absence of *Salvinia* spores. Charcoal particles were observed at
456 depths of 42 and 43 cm.

457 Zone ARA-III (39.5 – 18.5 cm; 21 samples; 1972 to 1989 AD) - AP increased continuously
458 from 30% to 82% but then dropped to 35% at the top of the zone. The most abundant arboreal
459 pollens were *Mimosa caesalpinifolia* (10-71%), *Mimosa tenuiflora* (5-40%), *Piptadenia*
460 *stipulacea* (2-7%), *Anadenanthera colubrina* (0-2%), *Combretum* (0-3%) and *Myracrodruon*
461 *urundeuva* (0-9%). NAP had a minimum of 13% in the lower part of the zone but increased to
462 64% toward the top. Among herbaceous taxa, *Alternanthera* (5-32%) and Poaceae (2-22%)
463 pollen were abundant. Pollen of *Borreria* (0-3%), *Mitracarpus* (0.3-5%), Asteraceae (0.3-
464 5%), Urticaceae (0-3%), *Acalypha* (0-4%) and *Zea mays* (<1%) were also well represented.
465 Pollen from drought tolerant tree taxa showed an increasing trend from 11% to 46%. In this
466 zone, taxa from the moist semi-deciduous forest group were represented by lower pollen
467 frequencies, between 0% and 4%, mainly because of very low values of Myrtaceae (<1%).
468 Percentage values of *Attalea speciosa* pollen (<1%) and *Copaifera* (<1%) remained low,
469 whereas Arecaceae (0–3%) pollen grains became more frequent. Taxa that grow on the dam
470 banks also reached higher values, mostly due to increasing percentages of Cyperaceae (2-
471 10%) and *Cleome* pollen (0-4%). Aquatics taxa were represented by increasing *Echinodorus*
472 (0.3-5%) pollen and *Salvinia* (<1%) spores. The amount of microscopic charred particles
473 increased during this period.

474 Zone ARA-IV (18.5 - 0 cm; 9 samples; 1989 to 2002 AD) - AP predominated with
475 frequencies ranging from 53% to 71%, whereas NAP decreased, ranging from 26% to 38%.
476 Percentages of *Mimosa caesalpinifolia* pollen remained high (17-46%). The increase in
477 pollen from drought tolerant tree taxa from 20% to 38% was mainly due to higher values of
478 *Mimosa tenuiflora* (10-23%) and *Piptadenia stipulacea* pollen (1-13%). Pollen abundances
479 of *Anadenanthera colubrina* (0-3%) and *Myracrodruon urundeuva* (1-4%) increased slightly,
480 while percentages of *Combretum* pollen (up to 2%) remained low. *Poincianella bracteosa*
481 pollen appeared for the first time at a depth of 15 cm. Herbs were characterized by decreasing
482 values of *Alternanthera* (1–8%) and Poaceae (5-12%), and percentages of pollen from other
483 herbaceous taxa continued to be low. Pollen of *Borreria* (1-4%) and *Mitracarpus* (2-6%)
484 increased in the upper part of this zone. Proportions of seasonal semi-deciduous forest taxa
485 decreased from 2% to 0%. Pollen frequencies of Cyperaceae increased to 17% while per-
486 centages of *Cleome* (<2%) decreased in this zone. Aquatic taxa remained stable at (2-6%).
487 No charcoal particles were counted in this zone.

488

489 **4. Discussion**

490 **4.1 Effects of climate variability**

491

492 Interannual rainfall variability does not reflect unequivocally in any of both records. Changes
493 in the geochemical proxies Si and Zr identified in facies 2, revealed four terrigenous events in
494 both records although the timing was different, showing an increase in erosion probably
495 linked to either extreme precipitation events or to agricultural activities (Hounsou-gbo et al.
496 2015; Wilhelm *et al.* 2012). At ACA15, these events match periods of increased precipitation
497 in the years 1982-83, 1987-88, 1992-96 and 2006-2012, with associated age model
498 uncertainties, that can be clearly observed in the sediment sequence but less in the vegetation

499 composition (Fig. 4). Between AD 1969 and 1981 (pollen zone ACA-II; Fig. 6) there was a
500 significant increase in the tree taxon *M tenuiflora* although this zone includes two climatic
501 intervals: the interval 1969 to 1974 with above normal rainfall, with six months of more than
502 50 mm/month, and the interval 1975 to 1980 with below average rainfall (Appendix B).
503 Between AD 1997 and 2015, the arboreal (37-63%) taxa remained stable even though this
504 zone includes the driest phase of the entire study with only two years with consecutive above-
505 average rainfall (1999 - 2000 and 2008 - 2009), of which only 2009 had significantly more
506 rain. Over the last 15 years, above average rainfall was only recorded in three years (2008,
507 2009 and 2011). In the years 2012, 2014 and 2015, the recorded rainfall values resembled
508 those during the severe droughts in 1966 and 1983. But despite several consecutive years of
509 below normal rainfall, rains were well distributed over five to six months with ≥ 50
510 mm/month (Appendix B) unlike in 2012 and 2015 when the little rain that fell was distributed
511 over three months. In 2014, even with four rainy months, the standard deviation of the annual
512 mean precipitation was the lowest since 1963.

513 In ARA15, the four observed terrigenous events in 1964.5 ± 10.5 yr AD, 1972 ± 9 yr AD,
514 1976 ± 8 yr AD, 1980 ± 7 yr AD (Fig. 4) do not match the major reservoir overflows that were
515 observed twelve times between 1978 and 2011 (Fig. 10, 11). Between 1960 and 1980 the tree
516 cover progressively increased either due to the absence of major drought episodes during this
517 interval or to an increase in local moisture due to the construction of the dam (Fig. 3, 10, 11).
518 We observed changes in the vegetation with a sharp decrease in *M caesalpiniifolia* during the
519 1982 drought followed by re-expansion during the rainy interval in 1984-85 (Fig. 11).
520 Between AD 1990 and 2002, the Caatinga tree taxa increased and showed the highest values
521 of the whole record. No major changes in vegetation were observed during the drought in
522 1992–1993, whereas a sharp decline in *Piptadenia stipulacea* was observed during the
523 drought in 1998, a decrease in *M caesalpiniifolia* was observed during the drought in 2001-

524 2002, whereas *M tenuiflora* continued to expand progressively (Fig. 8, 9, 11). These results
525 show that at the decadal scale Caatinga tree taxa have generally always been well represented
526 irrespective of the mean annual climatic conditions and highlight the resilience of this
527 ecosystem, which is well adapted to the alternance of drought and high moisture episodes.
528 Therefore, rainfall variability was not the primary driver of vegetation and land cover and
529 human activities have to be taken into consideration.

530 At a multidecadal scale, the progressive increase in tree pollen taxa *C leprosum* at ACA and
531 *M tenuiflora* at ARA (Fig. 7, 9) followed the same pattern as tropical Atlantic SST (Fig. 11).
532 Given the close link between SST and climate in the Ceará (Alves et al., 2009; Hounsou-gbo
533 et al., 2015), we can infer that these plant taxa responded to regional changes in temperature
534 and/or rainfall. Thus, the internal floristic composition of the Caatinga is likely to evolve
535 progressively as a function of changes in the SST.

536

537 **4.2 Human impacts**

538 Bromine (Br) in the sediment was associated with organic matter and used as a proxy for
539 organic content (Bajard et al. 2016), confirmed by the correlation between LOI550 and Br
540 contents (Fig. 5) with a similar increase in the upper part of ACA15 around 1987 and since
541 2003. XRF concentration of manganese (Mn) is an indicator for redox processes and rapid
542 changes in oxic-anoxic conditions at the water- sediment interface (Davison, W., 1993;
543 Deflandre et al. 2002; Elbaz-Poulichet et al. 2014). Abrupt changes can be caused by flood
544 events that may favor re-oxygenation of bottom water (Wilhelm et al. 2012). In organic rich
545 lake environments with hypoxic conditions caused by the decomposition of organic matter, an
546 increase in Mn may be observed during abrupt re-oxygenation of the sediment/water interface
547 linked to mass movement of water (Wirth et al. 2013). In ACA15, we observed both
548 indicators (organic matter and oxygenation; Fig. 11) since 2003 suggesting that this lake

549 system experienced a change in trophic status with an increase in in-lake productivity and
550 more hypoxic conditions. Consequently two distinct lacustrine phases were observed: 1) a
551 first one between 1961 and 2003 with fine sedimentation and flooding evidenced by
552 terrigenous material and occasional precipitation of Mn caused by re-oxygenation due to
553 flood events (Wilhelm et al. 2012); 2) a second phase between 2003 and 2015 with a change
554 in trophic status possibly related to the development of fisheries (Gurgel and Fernando, 1994)
555 and to the increase in population around the lake (20% increase between 1999 and 2003) (Fig.
556 10, 11). Many reservoirs created in the BSA in the second half of the 20th century currently
557 suffer from eutrophication and no longer provide drinkable water (CGEE 2017).
558 Today, the region around ACA is a vast area of intensive agriculture. Pollen of Arecaceae,
559 *Cecropia* sp. (a pioneer indicator of deforestation of the semi-deciduous forest) and
560 *Anacardium occidentale* (cashew) appeared often in the last 20 years, while pollen of
561 Sapindaceae, *Copaifera* sp. and *Attalea* sp. (Babaçu a species of palm that produces oil) were
562 found for the first time after 1963. Cashew and native babaçu palm are cultivated in the Serra
563 da Meruoca for commercial purposes (Coradin et al. 2018). Despite the creation of the Serra
564 da Meruoca Environmental Protection Area in 2008 (Law N° 11891), some families
565 continued to practice subsistence farming there.
566 At ARA local deforestation are shown by the increase in charcoal particles with a peak in
567 1983 and of cultivated taxa such as *Zea mays* (Fig. 8, 9).

568

569 **4.3 Effects of public policies**

570 The date of occurrence of the different events discussed below integrate the error interval
571 defined by the age model when comparing with the launching of the public policies (Fig. 2).
572 In ARA, before 1958, when the reservoir was not yet active, low tree pollen frequencies (less
573 than 5%) characterized a dry open landscape with abundant dry herbaceous taxa (mainly

574 Amaranthaceae *Alternanthera* sp. and Rubiaceae *Mitracarpus* sp.) (Fig. 8, 9). This interval
575 reflects the nature of the landscape before and during the construction of the dam that started
576 in 1951 and was inaugurated in 1958. The decrease in Zr content, a geochemical indicator
577 associated with coarse element represented by medium sand (facies 3 and Fig. 4, 11) was
578 evidence for the installation of the lacustrine system due to the construction of the dam. After
579 the dam began functioning, the main changes in the vegetation between AD 1963 and 1971
580 were reforestation with the expansion of the Caatinga tree species mainly *M caesalpinifolia*,
581 *M tenuiflora* and *Myracrodruon* sp. and an abrupt decrease in the herb taxa. Two more humid
582 periods in 1987 and 1994 were visible through geochemical proxies (Fig. 11). In 1986, the
583 irrigation law for northeastern Brazil was passed (Lei 10 Setembro 1986 Programa de
584 Irrigação do Nordeste – PROINE) resulting in a significant extension of the cultivated area
585 with, in particular in the hydrolic basin of Varjota, the Araras Norte Project that included 1
586 346 irrigated ha destined for fruit production (Ximenes and Furtado, 2018). The highest
587 concentration of Br recorded in 1987 related to an increase in organic matter in the lake likely
588 due to the erosion of soil litter. The implementation of the irrigation plan was associated with
589 a sharp prolongation of the local deforestation as evidenced by the decrease in *M*
590 *caesalpinifolia* and *M tenuiflora*, more frequent microscopic charred particles associated with
591 increased burning (Fig. 9) and the expansion of cultivated crops (Fig. 9). Remote sensing
592 reconstructions for the year 1999 show an increase in natural vegetation cover related to high
593 moisture rates while in 2016, after four years of very low rainfall, a significant reduction in
594 vegetation cover and an increase in bare soil emphasize the limits of the above mentioned
595 irrigation plan (Fig. 12).

596 At ACA, between 1980 and 1988, the vegetation cover became more open with a decline in
597 trees and shrubs, and more particularly in *M caesalpinifolia* despite years with abundant
598 rainfall after the severe drought of 1982-83 (ACA-III in Appendix B; Fig. 10, 11). Human

599 activities were triggered by the award of public contracts (Portaria nº 3 - DGO 22/02/1985)
600 for the use of land located upstream and downstream of the dam. The purpose of the land
601 concession agreement for agriculture and livestock was to settle farming families in the
602 vicinity of the public dams. Confirming fossil data, the satellite image from 1985 clearly
603 shows the impact of the law (Fig. 12, Table 1). Reforestation began in 1988, but the years
604 1990 to 1993 showed negative standard deviation of the annual mean precipitation,
605 culminating in another severe drought in the year 1993. Here again, analyses of a satellite
606 image acquired in 1991, which shows the return of a natural vegetation cover and a reduction
607 in the extent of bare soil, support the significant rise in tree pollen taxa (30-61%) mainly *M*
608 *caesalpiniifolia* between 1990 and 1997 (Fig. 12, Table 1). In 1989, the return of vegetation
609 cover was favored by the abandonment of cultivated land due to another law (National
610 Institute for Colonization and Agrarian Reform INCRA Law 97.844 19/07/1989).

611

612 **5. Conclusions**

613 Our study demonstrates the possibility of reconstructing the disturbances caused by human
614 activities and climatic changes in a hydrographic basin using sedimentary archives when
615 historical data are inexistent, rare or damaged. Despite similar climate variability, major
616 differences were observed between the two sites due to specific local human occupation and
617 development policies. The ability to monitor these trends at a variety of scales provides
618 crucial information for sustainable resource management decisions that are essential for the
619 maintenance and improvement of human wellbeing in the BSA (Wu, 2013). Three levels of
620 changes were observed depending on the duration of their impact on the landscape, annual,
621 decadal or pluridecadal. In the Acaraú basin, the high climatic variability in recent decades
622 did not seem to affect the composition of the Caatinga vegetation due to its extremely high
623 resilience. As models have difficulty predicting the response of this natural rainfall regime to

624 increasing land and sea temperatures (Marengo and Bernasconi, 2015), accurate monitoring is
625 needed before appropriate solutions for both people and the environment can be proposed. We
626 emphasize that public policies play a significant role in changes in the landscape and in
627 resources in the long term, whereas interannual climate variability and gradual climate change
628 have not affected the vegetation cover of the Caatinga in the last 60 years. It is now crucial to
629 define new forms of management that account for the physical, societal and sustainability
630 specificities of the BSA and, to promote sustainable land use when scarce water resources and
631 increasing temperatures threaten all the living organisms in these extreme conditions.

632

633 **Data availability**

634 The sequences reported in this paper will be deposited at the french national data repository
635 Cyber carothèque <https://cybercarotheque.fr/> with a link to PANGEA data base.

636

637 **Author contribution**

638 MPL and FSA defined the research objectives VJP performed the pollen analyses LB
639 collected the samples PS, ALD performed the geochemical analyses, FRGB performed the
640 charcoal analyses, ESPRM provided the climatic data, MRFF, DPF performed the image
641 analyses, CF built the synthetic figures All the authors wrote and commented on the
642 manuscript. All the authors read and approved the manuscript for submission.

643

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831

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837 **List of Figures**

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853 the plan 1-2, colored according to the sedimentological facies they belong to: black dots,
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862 matter content. LOI550 (E) has been added to show the covariation between LOI550 and
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882 analysis. Hollow curves correspond to an *exaggeration* x10.

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908 2007 and 2016, and (B) in the Araras basin in 1973, 1985, 1999 and 2016 extracted from
909 Landsat imagery.

910

911 Table

912 Table S1

913

Year	Natural vegetation cover km ²	Land use km ²	Reservoir km ²
ACA			
1981	257.65	226.29	8.74
1985	290.81	193.6	8.29
2007	359.65	124.53	8.49
2016	343.44	144.09	5.13
ARA			
1973	2643.96	714.15	66.55
1985	2821.7	606.5	95.54
1999	3141.96	324	53.51
2016	2155.39	1353.39	11.81

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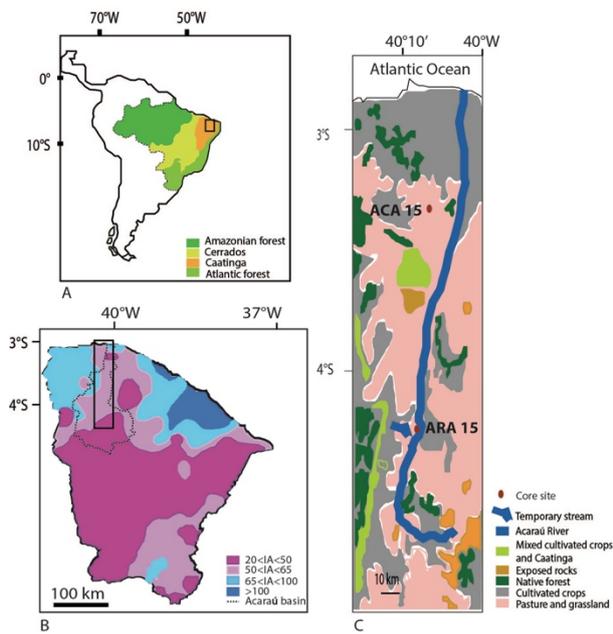
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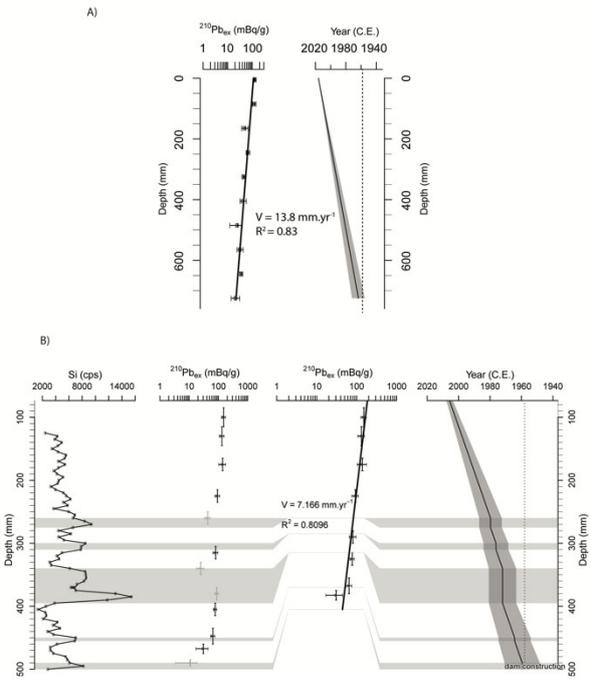
919 Figures

920 Figure 1



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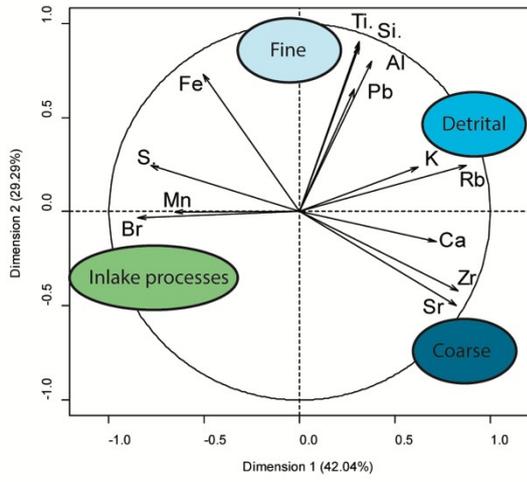


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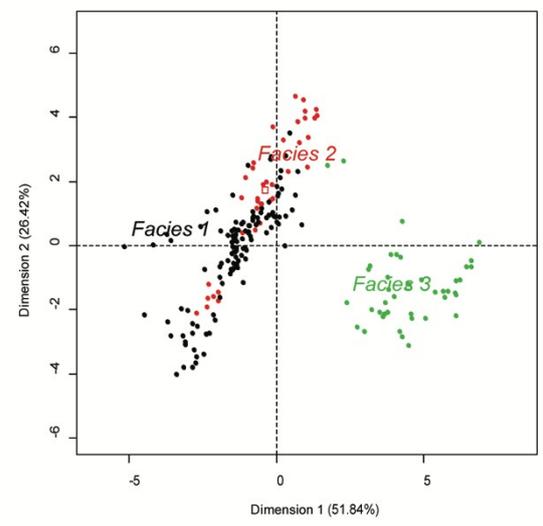
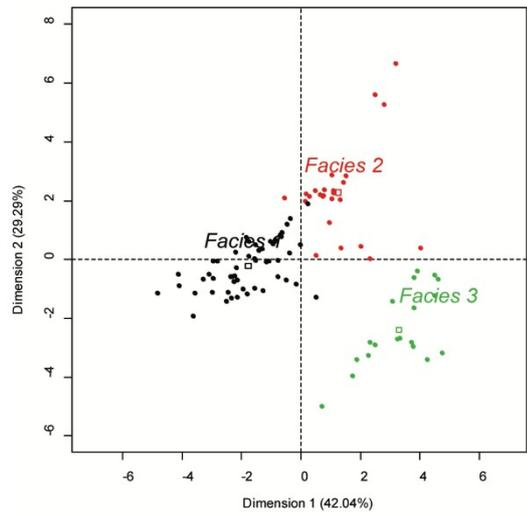
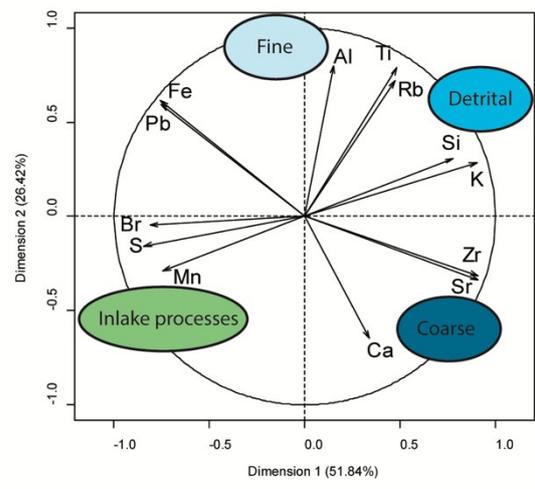
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925 Figure 3

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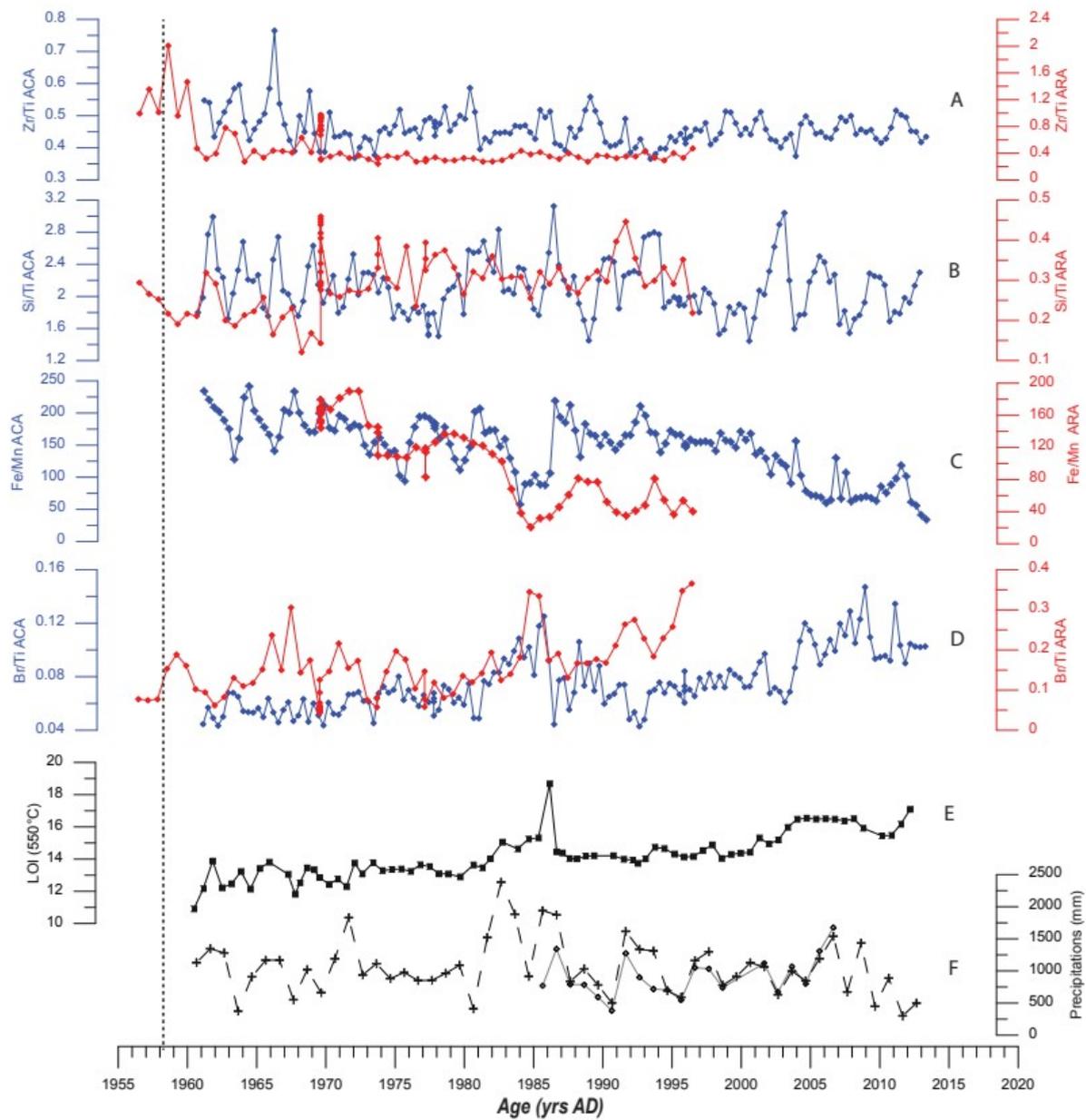


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927 Figure 4



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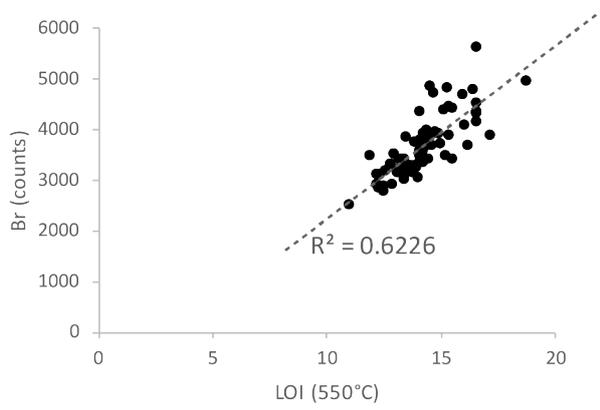
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932 Figure 5

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Bromine & LOI550 correlation



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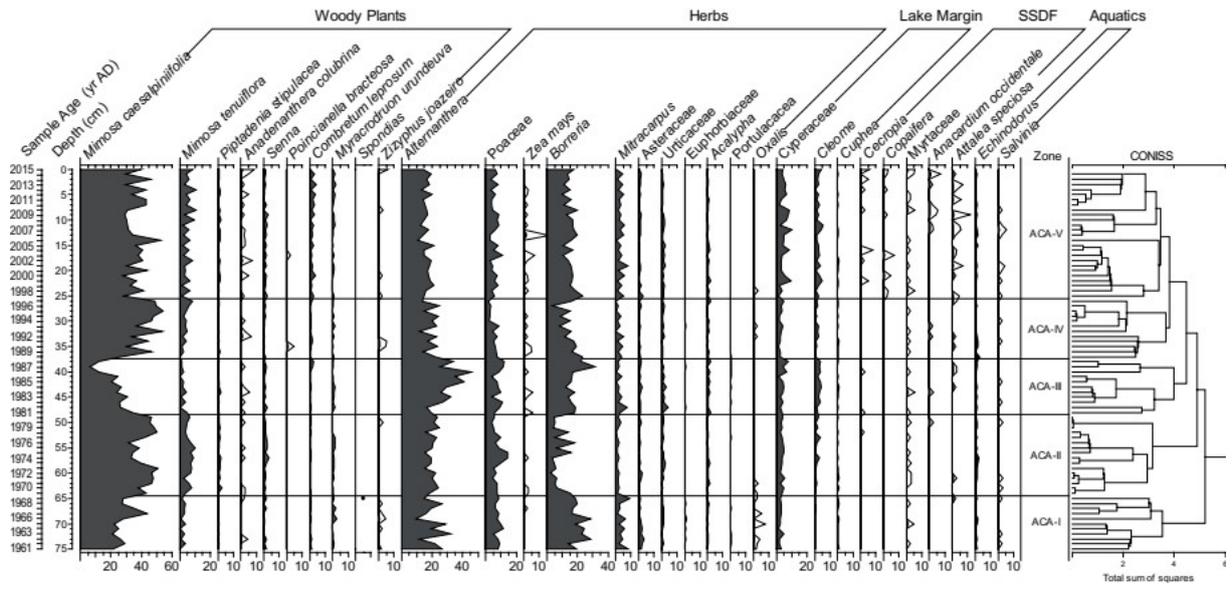
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951 Figure 6

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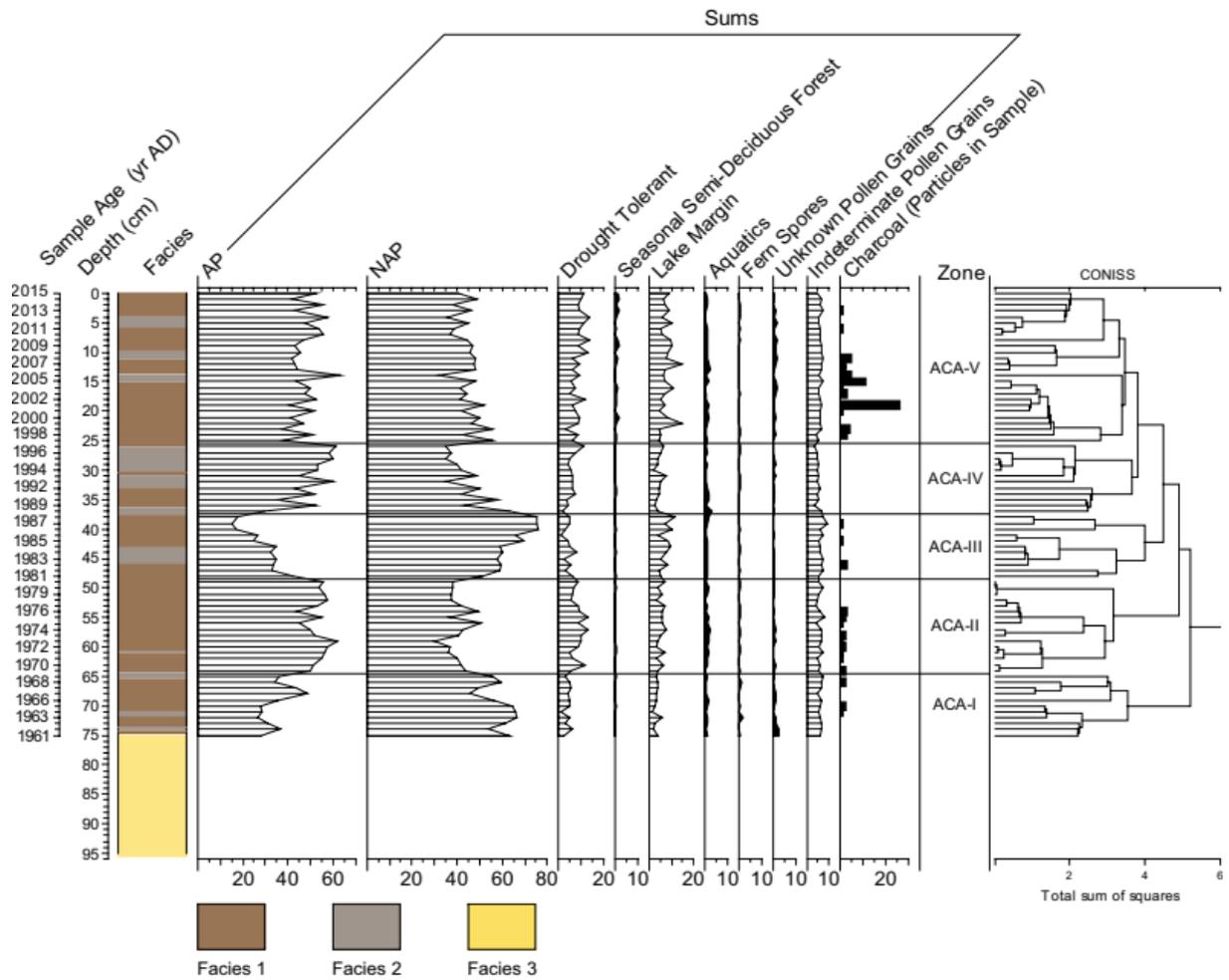
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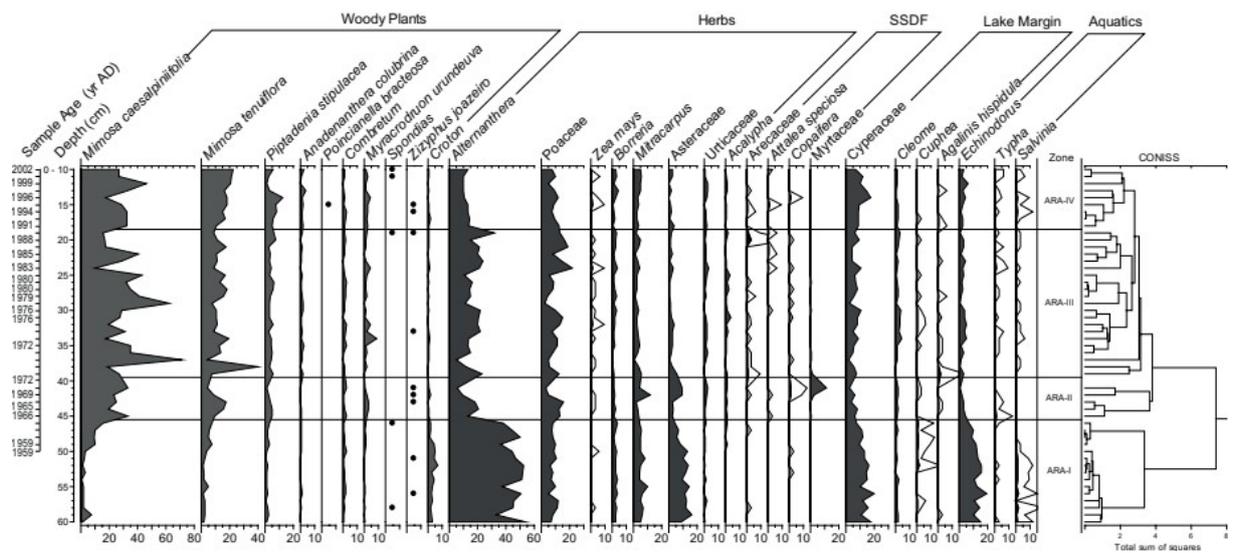
954 Figure 7



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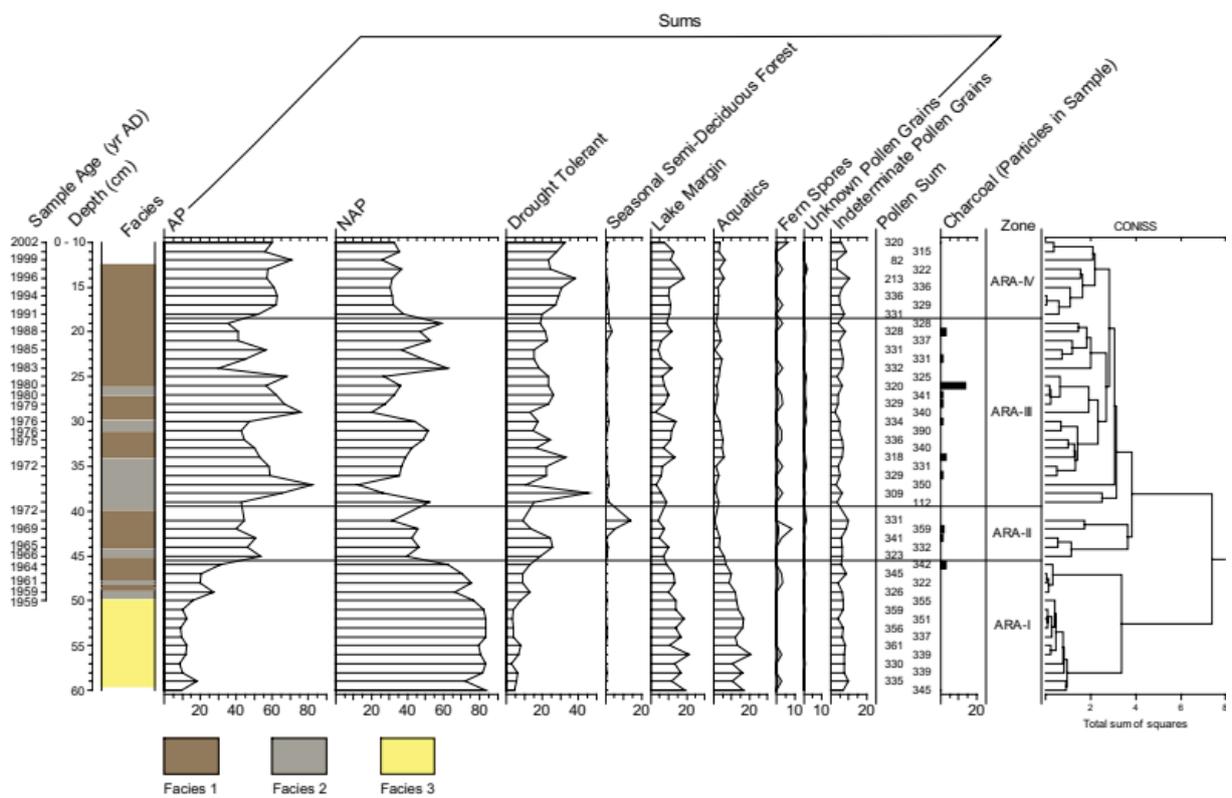


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960 Figure 9



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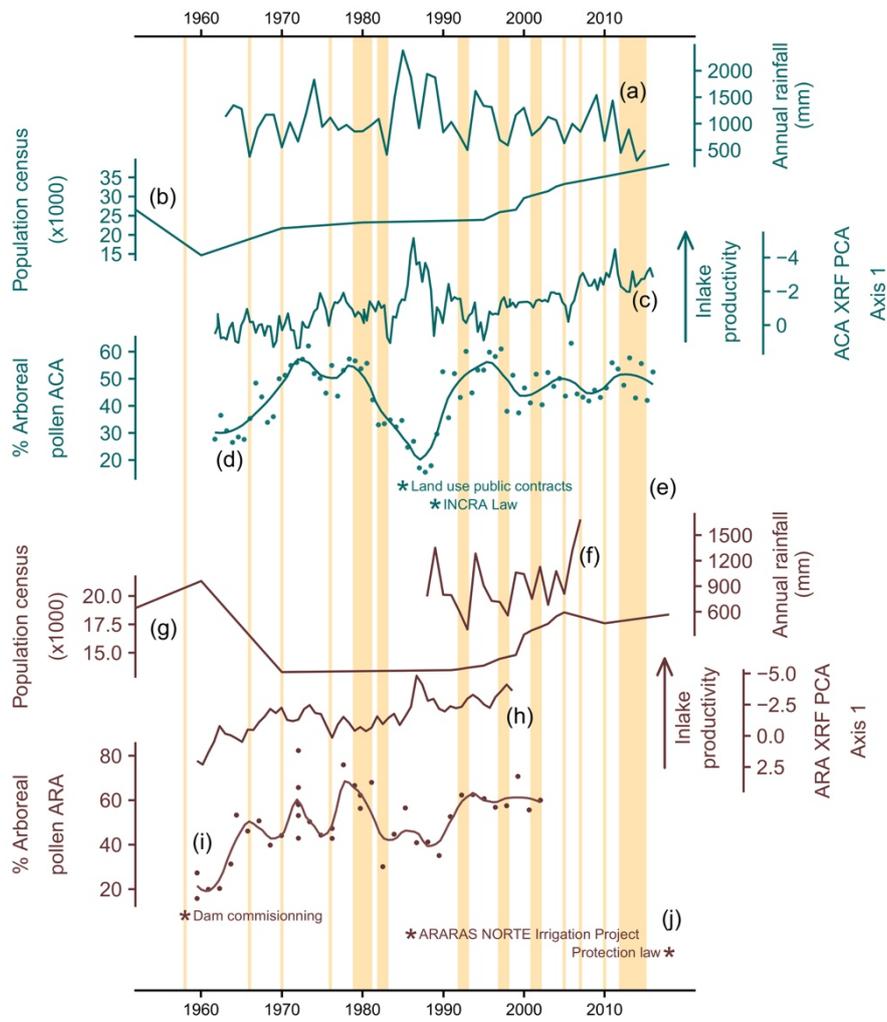
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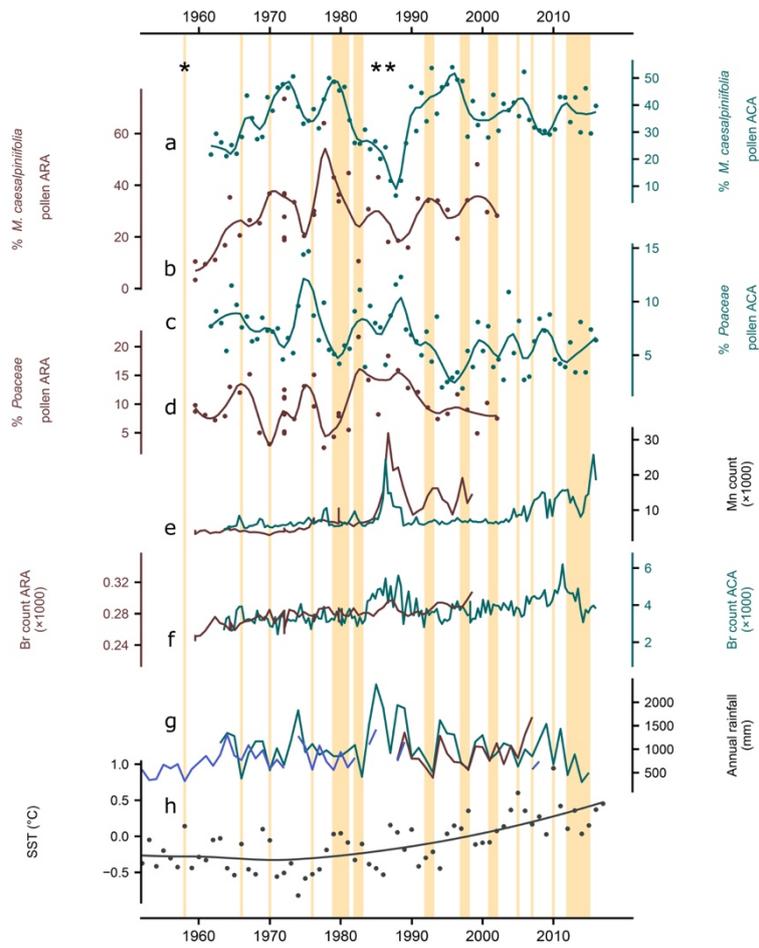
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964 Figure 10





966 Figure 11

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