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Climate change facilitated the early colonization of the Azores Archipelago during Medieval times.

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67 **Abstract**

68 Humans have made such dramatic and permanent changes to Earth's landscapes that much of it
69 is now substantially and irreversibly altered from its pre-anthropogenic state. Remote islands,
70 until recently isolated from humans, offer insights into how these landscapes evolved in response
71 to human-induced perturbations. However, little is known about when and how remote systems
72 were colonized because archaeological data and historical records are scarce and incomplete.
73 Here we use a multi-proxy approach to reconstruct the initial colonization and subsequent
74 environmental impacts on the Azores Archipelago. Our reconstructions provide unambiguous
75 evidence for widespread human disturbance of this archipelago starting between 700_{-60}^{+50} and
76 850_{-60}^{+60} CE, ca. 700 years earlier than historical records suggest the onset of Portuguese
77 settlement of the islands. Settlement proceeded in three phases, during which human pressure
78 on the terrestrial and aquatic ecosystems grew steadily (i.e., through livestock introductions,
79 logging and fire), resulting in irreversible changes. Our climate models suggest that the initial
80 colonization at the end of the Early Middle Ages (500 – 900 CE) occurred in conjunction with
81 anomalous northeasterly winds and warmer Northern Hemisphere temperatures. These climate
82 conditions likely inhibited exploration from southern Europe and facilitated human settlers from
83 the northeast Atlantic. These results are consistent with recent archaeological and genetic data
84 suggesting that the Norse were most likely the earliest settlers on the islands.

85 **Significance Statement**

86 We use a diverse set of lake and landscape proxy indicators to characterize initial human
87 occupation and its impacts on the Azores Archipelago. The occupation of these islands began
88 between 700 and 850 CE, 700 years earlier than suggested by official documentary sources.
89 These early occupations caused widespread ecological and landscape disturbance, and raise
90 doubts about the islands' presumed pristine nature during Portuguese arrival. The earliest
91 explorers arrived at the end of the Early Middle Ages, when temperatures were higher-than-
92 average, and the westerly winds were weaker, facilitating arrivals to the archipelago from
93 northeastern Europe and inhibiting exploration from southern Europe. This is consistent with
94 recent archaeological and genetic research suggesting the Norse were the first to colonize the
95 Azores Archipelago.

96

97 **Introduction**

98 The Azores Archipelago (36.5°- 40°N – 24.5°- 31.5°W) is made up of nine volcanic islands in the
99 North Atlantic (Fig.1), and given their distance from the European coast (ca. 1450 km), the
100 colonization of these islands would only have been possible after the advent of ocean-worthy ships
101 (1). Until recently, the consensus has been that the Azores were not colonized until the Portuguese
102 arrived between 1427 CE (Santa Maria Island) and 1452 CE (Flores and Corvo Islands) (2–5),
103 while searching for new routes to Asia (6). Historical documents from the first settlers note the
104 apparent pristine and undisturbed character of the islands (2, 3, 7). However, the presence of the
105 Azores archipelago on maps such as those of Pizzigani (1367 CE), the Medici-Laurentian (1370
106 CE), the Catalan (1375 CE), the Pinelli–Walckenaer (1384 CE), the Corbitis (c. 1385–1410 CE)
107 Atlas, as well as their listing in the Libro del Conoscimiento (c. 1380 CE), suggests that these
108 remote islands were well-known before their official settlement recorded in Portuguese historical
109 documents. This, raises questions both about the timing of the first human arrivals to the islands
110 and the pristine nature of these systems at that time.

111 To improve our understanding of the early colonization history and subsequent environmental
112 impacts of early settlers on the Azores, we studied sediment cores from lakes on five islands in
113 the Archipelago (Fig.1): Lake Caldeirão (Corvo Island; 39.7023° N - 31.1080° W; 400 m asl),
114 Lake Funda (Flores Island; 39.4475° N - 31.1939° W; 360 m asl), Lake Peixinho (Pico Island;
115 38.4580° N - 28.3228° W; 870 m asl), Lake Ginjal (Terceira Island; 38.7216° N - 27.2206° W; 390
116 m asl), and Lake Azul (São Miguel Island; 37.7804° N - 25.4970° W; 260 m asl). Age models for
117 each of the records were generated using a combination of ^{210}Pb, ^{137}Cs, and radiocarbon dating
118 (see Methods). The records vary in length, with the shortest records extending back to ~600 yr
119 cal. BP (Azul, Ginjal), while others cover the last ~1000 yr cal. BP (Funda), ~2700 yr cal. BP
120 (Peixinho) and the longest to ~3800 yr cal. BP (Caldeirão). Only the last two cover the time range
121 hypothesized for the Norse arrival in the Azores, but all records cover at least the last six hundred
122 years of historical human occupation. Collectively, these records provide integrative and novel
123 insights into the human settlement process and its environmental impacts across five different
124 islands that span 600 km along a range of physiographic settings (i.e., altitude, area, orography,
125 and hydrology) in the North Atlantic Ocean.

126 Lake sediments can provide robust, continuous, and high-resolution archives of environmental
127 changes (8). Disentangling the effects of climate change and anthropogenic activities on the
128 environment is, however, a major challenge because the signal of past anthropogenic activity is
129 often difficult to differentiate from the impacts of climate variability. To overcome this challenge,
130 we use faecal sterol biomarkers, coprostanol (5β-cholestan-3β-ol) and 5β-stigmastanol, as well
131 as coprophilous fungal spores (*Sporormiella*-type, *Sordaria*-type and *Podospora*-type; see
132 Methods) to identify human activities, related to the introduction of large herbivorous mammals
133 (i.e., livestock) (9). Sterols are abundant in mammal faeces, and coprostanol is particularly
134 abundant (~60%) in human faeces and other omnivores (10, 11). Although we interpret
135 coprostanol as an indicator for human activity, we cannot distinguish whether it was produced by
136 humans or introduced omnivores. In contrast, faeces from ruminants, such as cows and sheep,
137 contain proportionally higher concentrations of 5β-stigmastanol (11, 12). Coprophilous fungi life
138 cycles depend on herbivorous mammals as they ingest the spores during feeding and then are
139 released in the dung where the fungi grow and sporulate (13). Thus, spores from coprophilous
140 fungi are proxies for larger herbivores, which were not present on the Azores before humans
141 introduced livestock (14, 15). Together, these proxies provide unequivocal evidence for the
142 presence of humans and the introduction of ruminants to these oceanic islands. Since the earliest
143 arrivals may not have had sufficient human or ruminant population densities to leave a significant
144 imprint on lake records, we interpret these proxies as providing a minimum age for human arrival.

145 In addition to faecal sterols, and to assess the role of human settlement on landscape
146 degradation and ecological disruption, we also used a complementary set of proxy-based
147 indicators to simultaneously investigate human impacts on terrestrial and aquatic environments.
148 Variations in pollen, plant macrofossil, charcoal particles, and polycyclic aromatic hydrocarbons
149 (PAH) provide indicators of past vegetation change and fire disturbance (8, 16, 17). In addition,
150 major and trace element variations were used to assess changes in soil erosion (18). Similarly,
151 bulk and isotopic measurements of organic carbon and nitrogen reflect changes in terrestrial and
152 aquatic inputs (18). Distributions of fossil diatoms and chironomids were used as indicators of
153 ecological changes in the lake and catchment ecosystems (19, 20). Finally, to better understand
154 the climate conditions under which the early colonization of the Archipelago occurred (850 CE),
155 we use outputs from the Community Earth System Model (CESM-CAM5_CN) Last Millennium
156 Ensemble (LME) transient simulation (21).

157 Although ecological indicators of disturbance can be impacted by both anthropogenic and natural
158 drivers, we argue that the changes observed in our records are distinctly different than the
159 response to natural forcings. In records from Lake Caveiro (Pico island) and Lake Rasa (Flores
160 island) that span the mid-Holocene (~6000 yr and ~3000 yr long, respectively), episodic
161 increases in fire occur, presumably as a result of lightning ignition, or volcanic eruptions (22).
162 However, the terrestrial and aquatic ecosystem response to these events, reconstructed through
163 pollen and diatom proxies, is generally small, or in the case of eruptions, where impacts can be
164 significant, the recovery is relatively rapid (22, 23). By contrast, the alteration of natural drivers
165 had lasting impacts, mainly because native forests had little history of fire and little resilience to
166 the intensity of burning. This longer-term context for ecosystem variability demonstrates the
167 relative resilience of these oceanic island systems to natural climate change and highlights the
168 distinct impacts of human influences.

169 **Results and Discussion**
170 Using faecal biomarkers, we identified four phases related to the presence of human activity in
171 the sediment core records (Fig.2). During Phase I (500-700 CE), human activities are not
172 detected in any of the records. Phase II is defined by the first appearance of 5β-stigmastanol
173 between 700-1070 CE. Phase III is defined by the first appearance of coprostanol in the sediment
174 record after 1070 CE, and notable changes within the catchment areas, including increased fire
175 activity and soil erosion. Finally, coinciding with the official Portuguese arrival to the archipelago
176 (1427-1452 CE), Phase IV is defined by additional changes in the proxy records, such as a
177 decline in forested areas and lake eutrophication, that are still visible in the present-day
178 landscape.

179 The lack of faecal biomarkers during Phase I, suggests that humans and ruminants were absent
180 in the lake catchments areas before ~700 CE. Like most of the oceanic islands of Macaronesia,
181 except for the Canary Islands, the Azores Archipelago was devoid of non-volant mammals and
182 larger birds prior to the arrival of humans (15, 24). Pyrolytic PAHs and macrocharcoal display
183 relatively stable and low background levels during this period (accumulation rates of 1.34 ± 109
184 μg cm^{-2} y^{-1}; 0.3 ± 0.1 particles cm^{-2} y^{-1}, respectively), reflecting the low frequency of natural fires
185 in the lake catchments. Furthermore, the plant macrofossils and pollen data indicate that the
186 islands were densely forested with *Juniperus brevifolia* and *Ilex perado* in co-dominance with
187 *Myrsine africana* shrubs and mosses, which cover branches of trees and shrubs in this
188 environment (see *SI Appendix,* Fig. S1 – S6 and (25–27)). The maritime climate of the islands
189 would have contributed to a stable forest composition (23, 26). Environmental conditions within
190 the lake systems were also relatively stable, with lake organic matter dominated by allochthonous
191 sources and diatom communities of mostly oligo/mesotrophic taxa, indicating stable and relatively
192 low aquatic productivity (*SI Appendix,* Fig. S1 – S5 and Fig. S7).

193 The beginning of Phase II is defined by the first appearances of faecal biomarkers such as 5β-
194 stigmastanol at ca. 700±60 CE in the Lake Peixinho sedimentary record (50 ng cm^{-2} y^{-1} Pico
195 Island, Central Island Group), and at 850±60 CE in Lake Caldeirão (69 ng cm^{-2} y^{-1} Corvo Island,
196 Western Island Group). These biomarkers provide the most direct evidence, likely introduced
197 livestock (e.g. cattle, sheep, goats, and pigs), and provide the most direct evidence to date for the
198 first human activities on the islands (Fig. 2). Furthermore, given the distances between these two
199 islands (~ 260 km), the near synchronous appearance of the faecal markers in these two lake
200 systems suggests that, within chronological uncertainties, the arrival of early human settlers was
201 nearly synchronous across the archipelago.

202 The sudden and synchronous appearance of faecal biomarkers in the records on the distant Pico
203 and Corvo Islands contrasts with the lack of faecal biomarkers at Flores Island until 1300 CE,
204 although this island is only ca. 30 km south of (and visible from) Corvo Island. One possible
205 explanation could be hydrological differences. In contrast to Flores Island, neither Pico nor Corvo
206 Island have a well-developed surface hydrological system with permanent streams that transport
207 freshwater from the highlands to the shore. Consequently, highland lakes from Pico and Corvo
208 Island may have been the primary source of freshwater when the first settlements were
209 established, while they were probably less important when Flores Island was first occupied. In
210 addition, the patterns of human land use for volcanic islands usually follow an altitudinal
211 stratification resulting from a combination of a generally uneven orography and variation of bio-
212 climatic conditions with altitude (28, 29). This appears to be the case for the Azores Archipelago
213 islands in historical records (30) and could have also played a role during the early colonization of
214 these islands, with the first settlers only occupying and/or exploiting the islands' highlands when
215 strictly necessary.

216 Livestock faecal sterols are continuously present from 950_{-60}^{+50} CE onwards in Lake Peixinho,
217 although they show a more punctuated presence in Lake Caldeirão (Fig. 2). The simultaneous
218 increase of pyrolytic PAHs and macrocharcoal suggest that slash-and-burn techniques was used
219 to create suitable pastures for livestock close to the lake shores. This interpretation is reinforced
220 by the influx of arboreal plant macrofossils in Lake Caldeirão (*SI Appendix*, Fig. S1) and pollen in
221 Lake Peixinho (*SI Appendix*, Fig. S3), which show a sudden decline in juniper forests and an
222 expansion of grasses (Poaceae) at that time. Proxy-based indicators in lake sediments suggest
223 that the initial appearance of humans/livestock on the islands (Phase II; Fig. 2) was quickly
224 followed by large-scale landscape modifications and the introduction of large ruminants,
225 presumably associated with the establishment of permanent settlements.

226 The introduction of livestock and the practice of slash-and-burn agriculture had significant
227 ecological impacts on aquatic systems in the Azores Archipelago, as has been observed for other
228 island systems (31). The rise in the dominance of mesotrophic tychoplanktonic diatoms in Lake
229 Peixinho, together with the presence of profundal and low oxygen tolerance associated
230 chironomid taxa, and the decrease from 2.8 ± 0.4 ‰ to 1.9 ± 0.4 ‰ in δ^{15}N values, indicates a
231 rise in lake trophic state (see *SI Appendix*, Fig. S3). However, impacts on lake ecology appear to
232 be site dependent, with similar paleolimnological proxy indicators remaining relatively unchanged
233 in Lake Caldeirão at this time, perhaps because local settlements were either small or temporary.

234 The first appearance of coprostanol occurs at the beginning of Phase III at ca. 1070 CE in Lake
235 Peixinho (8.4 ng cm^{-2} y^{-1} Pico Island), and at 1280 CE in Lake Azul (6.5 ng cm^{-2} y^{-1} São Miguel
236 Island) (Fig. 2). Lake sediments of Pico, Corvo, Flores, and São Miguel islands all show a sharp
237 drop in arboreal pollen and a drastic increase of *Juniperus* leaf influx, in conjunction with an
238 increase in 5β-stigmastanol, coprophilous fungi, pyrolytic PAH, and charcoal particles (Fig. 2).
239 Taken together, this suggests that as human population pressure increased, deforestation
240 intensified to clear space for agriculture and livestock. The first appearance of *Secale cereale*
241 pollen grains ca. 1150 CE in Pico, ca. 1300 CE in São Miguel, and ca. 1550 CE in Corvo, as well
242 as *Plantago* spp. in Pico (ca. 1170 CE) and Corvo (ca. 1390 CE), corroborates this interpretation
243 (*SI Appendix,* Fig. S1-S5). These records provide unequivocal evidence of substantial human
244 occupation and are associated with unprecedented changes in the catchments and the lakes over
245 the last 1500 years. The intensification of human activities also resulted in an ecological regime
246 shifts in Lakes Caldeirão, Funda, and Peixinho as evidenced by accelerated sedimentation rates,

247 higher concentrations of terrigenous elements (Ti, Fe, Mn), and an increase in the relative
248 abundance of aerophilic diatoms of allochthonous origin (see *SI Appendix,* Fig. S1-S5). Increased
249 erosion and runoff from the catchment modified the supply of dissolved organic matter to the
250 lakes, increased nutrient availability, altered aquatic communities, and drastically increased lake
251 productivity. A decrease in sediment TOC/TN ratios at this time indicates a transition towards
252 more lacustrine-dominated organic matter in association with higher nutrient levels (*SI Appendix,*
253 Fig. S7).

254 The CESM Last Millennium simulations for this time interval suggest that the intensification of
255 anthropogenic pressures on local ecosystems occurred during a period of enhanced aridity partly
256 due to the predominance of positive phases of the North Atlantic Oscillation and East Atlantic
257 pattern (NAO$^+$/EA$^+$) (*SI Appendix*). Combined positive NAO and positive EA phases (*SI Appendix*,
258 Fig. S10) resulted in lower-than-average temperatures over Iceland, Greenland, and North Africa
259 and higher-than-average temperatures in the British Isles, Scandinavia, and eastern North
260 Atlantic (including the Azores Archipelago). Warmer and drier conditions at this time in the Azores
261 might have forced the inhabitants to exploit less accessible lakes located in the central and
262 highland areas of islands, such as on Flores Island, to aid in their survival, leading to an increase
263 in disturbance indicators in their sediment records.

264 Phase IV began with the historically documented arrival of the Portuguese to the Archipelago
265 between 1430 and 1450 CE and, consolidated the profound ecological transformation of
266 terrestrial and lacustrine ecosystems initiated during the previous phase (Fig. 2 and *SI Appendix,*
267 Fig. S1-S5). The steady decline of native arboreal pollen favored the appearance of grass
268 meadows mostly dominated by Poaceae. The continuous presence of coprophilous dung fungal
269 spores of *Sporormiella*-type in the sedimentary records evidence the intensification of human
270 activities including forest burning, cereal cultivation, and animal husbandry, as recorded in
271 Portuguese historical documents (2, 15). In contrast to previous intervals, this further
272 intensification of human activities often resulted in irreversible changes to lake trophic states.
273 Increased catchment erosion resulted in enhanced delivery of nutrients to most lakes, leading to
274 increased eutrophication, as indicated by a larger abundance of eutrophic diatom taxa, and the
275 development of a more permanent anoxic hypolimnion as evidenced by a reduction in chironomid
276 abundances (see *SI Appendix,* Fig. S1-S5). Successive introductions of fish in the fishless lakes
277 of the Azores after 1790 CE triggered a set of top-down (predation on zooplankton and
278 chironomids) and bottom-up (sediment-resuspension) controls, promoting a further shift towards
279 eutrophic conditions (32, 33).

280 The arrival of the Portuguese to the Azores occurred during the Little Ice Age (LIA; 1300-1850
281 CE, (34)). Simulations with CESM indicate that this interval was marked by a more dominant
282 NAO$^-$/EA$^+$ atmospheric winter configuration, resulting in a tendency towards more humid and
283 colder-than-average climate conditions on the Azores Archipelago (Figure 3 and *S11*). The shift
284 to wetter conditions is evident in the aquatic diatom records, particularly in the deeper lake
285 systems (i.e., Lakes Funda and, Azul). Despite the evidence for milder climate conditions at this
286 time, disturbance indicators still increase, demonstrating the severity of the impacts of
287 Portuguese settlement. However, the shift in climate conditions likely also enhanced surficial
288 runoff, exacerbating the anthropogenic effects on the freshwater ecosystems.

289 **Who first colonized the Azores?**
290 Our reconstructions offer unambiguous evidence for the pre-Portuguese settlement of the Azores
291 Archipelago and suggests that people first occupied the islands as early as the Early Middle Ages

8

292 (EMA; 500 – 900 CE), This finding builds upon other studies suggesting that the Portuguese may
293 not have been the first inhabitants of the islands. Previous work on lake sediments from Lake
294 Azul, on São Miguel Island, using pollen, charcoal and dung fungi as proxy-based indicators,
295 demonstrated that rye pollen together with spores from coprophilous fungi (*Sordaria,*
296 *Sporormiella, Cercophora, Podospora*) were continuously present after 1287 CE and were
297 interpreted as evidence of early cereal cultivation and livestock farming, respectively (25). Our
298 current study extends the timing of the earliest occupation by human back by an additional 500
299 years. Other recent data supports our new evidence for initial occupation in the Early Middle
300 Ages. For example, a recent radiocarbon date 903-1036 CE (1033 $\pm$ 28 yr BP uncalibrated) on
301 house-mouse (*Mus musculus*) bones collected at a fossil site on Madeira Island (35) and
302 colonization dates of 910-1185 CE for this species established by molecular dating methods
303 using mtDNA D-loop sequences (36) suggest that explorers had accidentally introduced this alien
304 species on several Macaronesian islands by this time (Azores, Madeira, and the Canary Islands).
305 Although controversial, radiocarbon dating of organic matter embedded in silica cement that
306 partially filled a putative human-made trachytic rock bowl from Terceira Island yielded an age of
307 1020 - 1160 CE (950 $\pm$ 30 cal. yr BP, 2-σ) (37). These studies are consistent with the first
308 appearance of faecal biomarkers in our records (Fig. 4).

309 Genetic characterization of modern Macaronesian *Mus musculus* populations present in the
310 Azores shows that this species followed a complex colonization history from multiple
311 geographical origins (38), with two of the mitochondrial D-loop sequences indicating an origin in
312 northern Europe (Denmark, Norway, Iceland, Ireland, Sweden, Finland, and the Faroe Islands)
313 (39). The observation that northern European mice contribute significantly to the Azorean mouse
314 gene pool suggests that they were amongst the earliest populations introduced to the island.
315 This strongly suggests that they arrived with the earliest settlers, from northern Europe, in the
316 early Middle Ages. An early discovery of the Macaronesian islands by the Norse from northern
317 Europe also provides a plausible explanation for the presence of the archipelago on maps before
318 the official Portuguese discovery. In fact, Corvo island appears as *Corvis Marinis* (Marine Raven
319 Island) in the Medici Atlas (1370 CE), suggesting that Northern people discovered it since these
320 northern explorers usually used ravens to help them locate landfalls when far out at sea (40).

321 To better understand the climatic and oceanic conditions under which this early arrival may have
322 occurred, we examined climate model simulations for the 850-1850 CE period using the CESM-
323 CAM5_CN from the LME (21). According to this climate model simulation, the end of the EMA
324 period was associated with a predominance of NAO$^-$/EA$^-$ phases (41, 42), with warmer and drier-
325 than-average decadal climate conditions (Fig. 3 and *SI Appendix,* Fig. S8). This prevailing
326 NAO/EA combination resulted in a Mean Sea Level Pressure (MSLP) dipole with severely
327 weakened westerly winds over all the North Atlantic (25 °- 65 °N) and an enhanced northerly wind
328 component following the N - S western European margin, from Scandinavia to the Iberian
329 Peninsula (Fig. 3 and *SI Appendix,* Fig. S11). The weakening of the westerlies associated with
330 anomalous NE winds would have facilitated the arrival of Norse explorers to the Archipelago,
331 while hindering more meridional explorers from reaching these islands. At that time, the Norse
332 started to colonize North Atlantic islands, with settlements in the Faroe Islands (ca. 800 CE),
333 Iceland (ca. 870 CE), Greenland (ca. 1000 CE), and Newfoundland (ca. 1000 CE) (43, 44).
334 Therefore, they had the knowledge and navigational skills required to sail in open ocean waters
335 and are the most likely candidates to have reached the Azores Archipelago during this period.
336 The lack of historical records prevents us from concluding whether their arrival on the Azores
337 Archipelago was intentional (very unlikely, as the first known maps detailing the approximate

338 location of the islands were drawn 500 years later) or accidental (more probable as storms and
339 anomalous NE winds might have sporadically pushed ships out of their common sailing routes).

340 The EMA's atmospheric configuration is different from what was typical of the time period when
341 the Portuguese officially colonized the Azores. Between 1430 and 1450 CE, the multi-decadal
342 dominance of the NAO$^-$/EA$^+$ phases led to weakened westerlies with prevailing SE winds that
343 favored navigation between southern Europe and the Azores Archipelago, while pushing northern
344 explorers towards the American continent (Fig. 3). This particular NAO/EA combination at the
345 onset of the LIA triggered an MSLP dipole with higher-than-usual MSLP values over Iceland and
346 lower-than-usual MSLP values over the central Atlantic. These MSLP anomalies gave rise to a
347 southern migration of an enhanced westerlies belt (< 30 °N), resulting in strongly weakened
348 westerlies between 35° and 60° N (see SI appendix). Therefore, the two main colonization pulses
349 were facilitated by weakened westerlies due to a NAO$^-$ phase predominance, whereas the
350 (negative or positive) EA pattern phase likely played a key role in determining who (Norse or
351 Portuguese) and when (9th or 15th centuries, respectively) the first explorers reached and settled
352 the Azores Archipelago.

353 The results of this study suggest that early settlers from northern Europe not only reached the
354 Azores several hundreds of years before the Portuguese, but that their settlements were
355 extensive enough to be evident in faecal biomarker records in sites throughout the archipelago.
356 Furthermore, these early settlements led to profound environmental and ecological disturbance
357 (8). These findings are in conflict with the reports of early Portuguese sailors, who described the
358 Azores as heavily forested and pristine. Given the much more extensive environmental
359 degradation which accompanied Portuguese arrival, it may be that comparatively unaltered
360 conditions of the islands appeared undisturbed to the first Portuguese settlers. This highlights the
361 challenge in relying on the historical record to identify relative states of ecosystems or landscape
362 disturbance (8). Another question raised by the data is the persistence of faecal biomarkers in the
363 lake records up to the time of Portuguese arrival, when there are no reports of human occupation
364 or introduced ruminants (2, 3). Such long-lasting occupations should be evident in the
365 archaeological record. More work on this possibility is needed in the future.

366 **Materials and Methods**
367
368 Coring campaigns were conducted in September 2011 (Lake Azul), July 2015 (Lake Peixinho),
369 June 2017 (Lakes Funda and Caldeirão), and August 2018 (Lake Ginjal) to retrieve the complete
370 sedimentary infill using a UWITEC piston corer installed on a UWITEC floating platform. Cores
371 were sealed entirely in the field and transported to Geo3BCN-CSIC (Barcelona, Spain). They
372 were split longitudinally, imaged with a high-resolution CCD camera, and their elemental chemical
373 composition determined every 2 mm using an AVAATECH XRF continuous core scanner at the
374 University of Barcelona. Cores were subsampled regularly to assess the content of pollen and
375 other non-palynological remains, micro, and macrocharcoal, chironomids, diatoms, bulk organic
376 matter composition (TOC and TN), isotope signatures (δ^{13}C and δ^{15}N), mineralogical
377 composition, and sterol and stanol analyses. See the SI Appendix for further details of the
378 methodologies and sampling intervals employed to characterize these proxies.

379 To understand the climate conditions under which changes in occupation and disturbance
380 occurred, we use results from the Last Millennium Ensemble (LME) using CESM-CAM5_CN. We
381 selected this model as it provides simulations using transient forcing mechanisms, and according
382 to its spatio-temporal resolution (2º horizontal and monthly) and the available climate variables

383   (mean sea level pressure, horizontal wind at the 925 hPa level, 2 m air temperature, and
384   precipitation). We acknowledge that these simulations start only at 850 CE, but we are unaware
385   of any similar simulations extending back to the previous century when our data suggest that first
386   occupation of the Azores occurred (i.e., 700-850 CE). Thus, we use the earliest available period
387   of simulation (850-900 CE) to characterize the conditions under which the initial colonization
388   occurred. Given the small changes in forcing applied in the transient simulations during these two
389   centuries (700-900 CE), we are confident that this should be a relatively close approximation to
390   the interval of interest. Further details related to the CESM simulations are detailed in the
391   supplementary material.

392   The chronological framework for the records was built using four ^{210}Pb and three ^{137}Cs profiles,
393   and 40 AMS ^{14}C dates. The statistical analyses of the proxy-based indicators and the age-depth
394   model for every record, integrating ^{210}Pb and ^{137}Cs profiles and the radiocarbon dating on plant
395   macrofossil remains, and pollen concentrates, were carried out using the version 2.3.9 of the R
396   Clam package (45, 46), (47). This package automatically calibrated all radiocarbon dates at 2-σ
397   using the IntCal20 calibration curve (48).

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Figure Legends

Figure 1. (A) Inset: Location of the Azores Archipelago in the North Atlantic. Red lines – Triple junction between North American, the Eurasian and the Nubian plates. (B) Large figure: Distribution of the islands in the Western Group (Corvo and Flores Islands), Central Group (São Jorge, Faial, Graciosa, Terceira, and Pico Islands), and Eastern Group (São Miguel and Santa Maria Islands). Islands and lakes from which sediment records have been studied are indicated. The dates for each lake correspond to the first appearance of unequivocal evidence of human activities (see text for further details).

Figure 2. Left – Faecal sterol biomarkers coprostanol (Blue bar) (5β-cholestan-3β-ol) and 5β-stigmastanol flux (Magenta bar) (ng cm^{-2} y^{-1}), Coprophilous fungi flux (Orange bar) (spores cm^{-2} y^{-1}), Arboreal pollen (%; Green line and silhouette),presence of Cerealea pollen (Yellow dot) and Sporormiella-type fungi (Star). Right - Total pyrolytic PAHs flux (Black bar) (ng cm^{-2} y^{-1}) and charcoal flux (Orange bar) (particles cm^{-2} y^{-1}). Western Group A) Lake Caldeirão (Corvo Island); B) Lake Funda (Flores Island); Central Group C) Lake Peixinho (Pico Island); D) Lake Ginjal (Terceira Island) and Eastern Group E) Lake Azul (São Miguel Island). Phases: I – Absence of faecal biomarkers; II – First appearance of faecal biomarkers; III – First appearance of coprostanol (5β-cholestan-3β-ol); IV – Official Portuguese arrival to Azores Archipelago. Grey bars, represent tephra layers.

Figure 3. North Atlantic average anomalies for Mean Sea Level Pressure (MSLP; blue/red lines), 2 m temperature (shading), and 925 hPa horizontal wind (vectors) during the 850 – 1500 CE period. **A)** Average anomalies for MSLP (blue/red lines), 2 m temperature (shading), and 925 hPa horizontal wind (vectors) during NAO$^-$/EA$^-$ prevailing conditions. Greenline - Norse maritime routes during the 9th-11th century. Blue rectangle – location of the Azores Archipelago (AZO). Dotted orange - a possible route of Norse reaching the Azores Archipelago. **B)** Average anomalies for MSLP (blue/red lines), 2 m temperature (shading), and 925 hPa horizontal wind (vectors) during NAO$^-$/EA$^+$ prevailing conditions. Magenta line - Portuguese maritime routes during 15th century. Blue rectangle – Azores Archipelago location.

Figure 4. Summary of evidence for earlier human activities and the timing of the Portuguese arrival in the Azorean Archipelago between 500 – 1800 CE.