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2 **Main Manuscript for**

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

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64 Main Text

65 Figures 1 to 4

66

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.<sub>-60</sub><sup>+50</sup> and  
76 850.<sub>-60</sub><sup>+60</sup> 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  
101 ships (1). Until recently, the consensus has been that the Azores were not colonized until the  
102 Portuguese arrived between 1427 CE (Santa Maria Island) and 1452 CE (Flores and Corvo  
103 Islands) (2–5), while searching for new routes to Asia (6). Historical documents from the first  
104 settlers note the apparent pristine and undisturbed character of the islands (2, 3, 7). However, the  
105 presence of the Azores archipelago on maps such as those of Pizzigani (1367 CE), the Medici-  
106 Laurentian (1370 CE), the Catalan (1375 CE), the Pinelli–Walckenaer (1384 CE), the Corbitis (c.  
107 1385–1410 CE) Atlas, as well as their listing in the Libro del Conoscimiento (c. 1380 CE),  
108 suggests that these remote islands were well-known before their official settlement recorded in  
109 Portuguese historical documents. This, raises questions both about the timing of the first human  
110 arrivals to the islands 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 <sup>210</sup>Pb, <sup>137</sup>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 (Fundá), ~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 (5 $\beta$ -cholestan-3 $\beta$ -ol) and 5 $\beta$ -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 5 $\beta$ -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 5 $\beta$ -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  $1.34 \pm 109$   
184  $\mu\text{g cm}^{-2} \text{y}^{-1}$ ;  $0.3 \pm 0.1$  particles  $\text{cm}^{-2} \text{y}^{-1}$ , 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 5 $\beta$ -  
194 stigmastanol at ca.  $700 \pm 60$  CE in the Lake Peixinho sedimentary record ( $50 \text{ ng cm}^{-2} \text{y}^{-1}$  Pico  
195 Island, Central Island Group), and at  $850 \pm 60$  CE in Lake Caldeirão ( $69 \text{ ng cm}^{-2} \text{y}^{-1}$  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.<sub>60</sub><sup>+50</sup> 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 tycho planktonic diatoms in Lake  
229 Peixinho, together with the presence of profundal and low oxygen tolerance associated  
230 chironomid taxa, and the decrease from  $2.8 \pm 0.4$  ‰ to  $1.9 \pm 0.4$  ‰ in  $\delta^{15}\text{N}$  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 ( $8.4 \text{ ng cm}^{-2} \text{ y}^{-1}$  Pico Island), and at 1280 CE in Lake Azul ( $6.5 \text{ ng cm}^{-2} \text{ y}^{-1}$  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  $5\beta$ -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<sup>+</sup>/EA<sup>+</sup>) (*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<sup>-</sup>/EA<sup>+</sup> 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



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,  $2-\sigma$ ) (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<sup>-</sup>/EA<sup>-</sup> 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<sup>+</sup> 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<sup>-</sup> 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 ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ), 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 (2° 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  $^{210}\text{Pb}$  and three  $^{137}\text{Cs}$  profiles,  
393 and 40 AMS  $^{14}\text{C}$  dates. The statistical analyses of the proxy-based indicators and the age-depth  
394 model for every record, integrating  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  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- $\sigma$   
397 using the IntCal20 calibration curve (48).

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406

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521 **Figure Legends**

522

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

530

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

541

542 **Figure 3.** North Atlantic average anomalies for Mean Sea Level Pressure (MSLP; blue/red lines),  
543 2 m temperature (shading), and 925 hPa horizontal wind (vectors) during the 850 – 1500 CE  
544 period. **A)** Average anomalies for MSLP (blue/red lines), 2 m temperature (shading), and 925 hPa  
545 horizontal wind (vectors) during NAO<sup>-</sup>/EA<sup>-</sup> prevailing conditions. Greenline - Norse maritime  
546 routes during the 9<sup>th</sup>-11<sup>th</sup> century. Blue rectangle – location of the Azores Archipelago (AZO).  
547 Dotted orange - a possible route of Norse reaching the Azores Archipelago. **B)** Average  
548 anomalies for MSLP (blue/red lines), 2 m temperature (shading), and 925 hPa horizontal wind  
549 (vectors) during NAO<sup>+</sup>/EA<sup>+</sup> prevailing conditions. Magenta line - Portuguese maritime routes  
550 during 15<sup>th</sup> century. Blue rectangle – Azores Archipelago location.

551

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

554

555