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

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Abstract

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

Significance Statement

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

Introduction

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

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

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

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

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

Results and Discussion

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

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

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

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

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

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

The first appearance of coprostanol occurs at the beginning of Phase III at ca. 1070 CE in Lake 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 Island) (Fig. 2). Lake sediments of Pico, Corvo, Flores, and São Miguel islands all show a sharp drop in arboreal pollen and a drastic increase of *Juniperus* leaf influx, in conjunction with an increase in 5β-stigmastanol, coprophilous fungi, pyrolytic PAH, and charcoal particles (Fig. 2). Taken together, this suggests that as human population pressure increased, deforestation intensified to clear space for agriculture and livestock. The first appearance of *Secale cereale* pollen grains ca. 1150 CE in Pico, ca. 1300 CE in São Miguel, and ca. 1550 CE in Corvo, as well as *Plantago* spp. in Pico (ca. 1170 CE) and Corvo (ca. 1390 CE), corroborates this interpretation (*SI Appendix,* Fig. S1-S5). These records provide unequivocal evidence of substantial human occupation and are associated with unprecedented changes in the catchments and the lakes over the last 1500 years. The intensification of human activities also resulted in an ecological regime shifts in Lakes Caldeirão, Funda, and Peixinho as evidenced by accelerated sedimentation rates, higher concentrations of terrigenous elements (Ti, Fe, Mn), and an increase in the relative abundance of aerophilic diatoms of allochthonous origin (see *SI Appendix,* Fig. S1-S5). Increased erosion and runoff from the catchment modified the supply of dissolved organic matter to the lakes, increased nutrient availability, altered aquatic communities, and drastically increased lake productivity. A decrease in sediment TOC/TN ratios at this time indicates a transition towards more lacustrine-dominated organic matter in association with higher nutrient levels (*SI Appendix,* Fig. S7).

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

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

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

Who first colonized the Azores?

Our reconstructions offer unambiguous evidence for the pre-Portuguese settlement of the Azores Archipelago and suggests that people first occupied the islands as early as the Early Middle Ages

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

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

To better understand the climatic and oceanic conditions under which this early arrival may have occurred, we examined climate model simulations for the 850-1850 CE period using the CESM-CAM5_CN from the LME (21). According to this climate model simulation, the end of the EMA period was associated with a predominance of NAO^{-}/EA^{-} phases (41, 42), with warmer and drier-than-average decadal climate conditions (Fig. 3 and *SI Appendix,* Fig. S8). This prevailing NAO/EA combination resulted in a Mean Sea Level Pressure (MSLP) dipole with severely weakened westerly winds over all the North Atlantic (25 °- 65 °N) and an enhanced northerly wind component following the N - S western European margin, from Scandinavia to the Iberian Peninsula (Fig. 3 and *SI Appendix,* Fig. S11). The weakening of the westerlies associated with anomalous NE winds would have facilitated the arrival of Norse explorers to the Archipelago, while hindering more meridional explorers from reaching these islands. At that time, the Norse started to colonize North Atlantic islands, with settlements in the Faroe Islands (ca. 800 CE), Iceland (ca. 870 CE), Greenland (ca. 1000 CE), and Newfoundland (ca. 1000 CE) (43, 44). Therefore, they had the knowledge and navigational skills required to sail in open ocean waters and are the most likely candidates to have reached the Azores Archipelago during this period. The lack of historical records prevents us from concluding whether their arrival on the Azores Archipelago was intentional (very unlikely, as the first known maps detailing the approximate location of the islands were drawn 500 years later) or accidental (more probable as storms and anomalous NE winds might have sporadically pushed ships out of their common sailing routes).

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

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

Materials and Methods

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

To understand the climate conditions under which changes in occupation and disturbance occurred, we use results from the Last Millennium Ensemble (LME) using CESM-CAM5_CN. We selected this model as it provides simulations using transient forcing mechanisms, and according to its spatio-temporal resolution (2º horizontal and monthly) and the available climate variables (mean sea level pressure, horizontal wind at the 925 hPa level, 2 m air temperature, and precipitation). We acknowledge that these simulations start only at 850 CE, but we are unaware of any similar simulations extending back to the previous century when our data suggest that first occupation of the Azores occurred (i.e., 700-850 CE). Thus, we use the earliest available period of simulation (850-900 CE) to characterize the conditions under which the initial colonization occurred. Given the small changes in forcing applied in the transient simulations during these two centuries (700-900 CE), we are confident that this should be a relatively close approximation to the interval of interest. Further details related to the CESM simulations are detailed in the supplementary material.

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

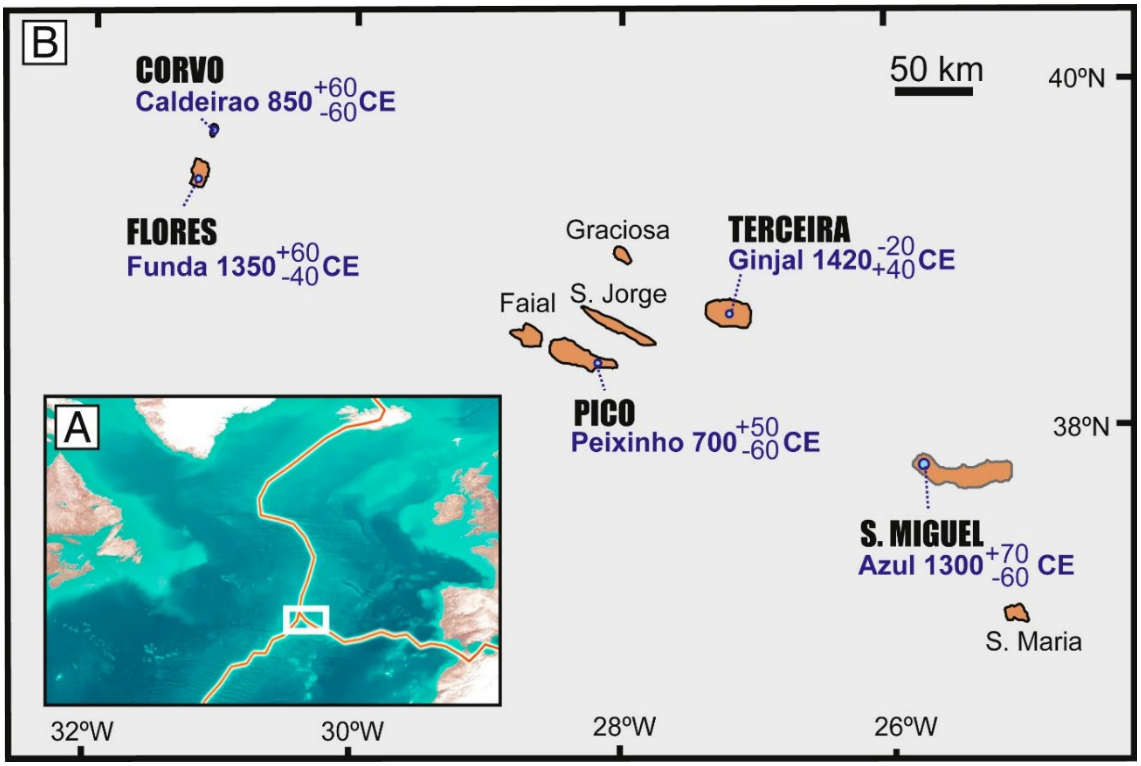
B
CORVO
Caldeirao 850 +60 -60 CE
FLORES
Funda 1350 +60 -40 CE
Graciosa
TERCEIRA
Ginjal 1420 -20 +40 CE
Faial
S. Jorge
PICO
Peixinho 700 +50 -60 CE
S. MIGUEL
Azul 1300 +70 -60 CE
S. Maria
50 km
40ºN
38ºN
32ºW
30ºW
28ºW
26ºW
A

Figure 1.

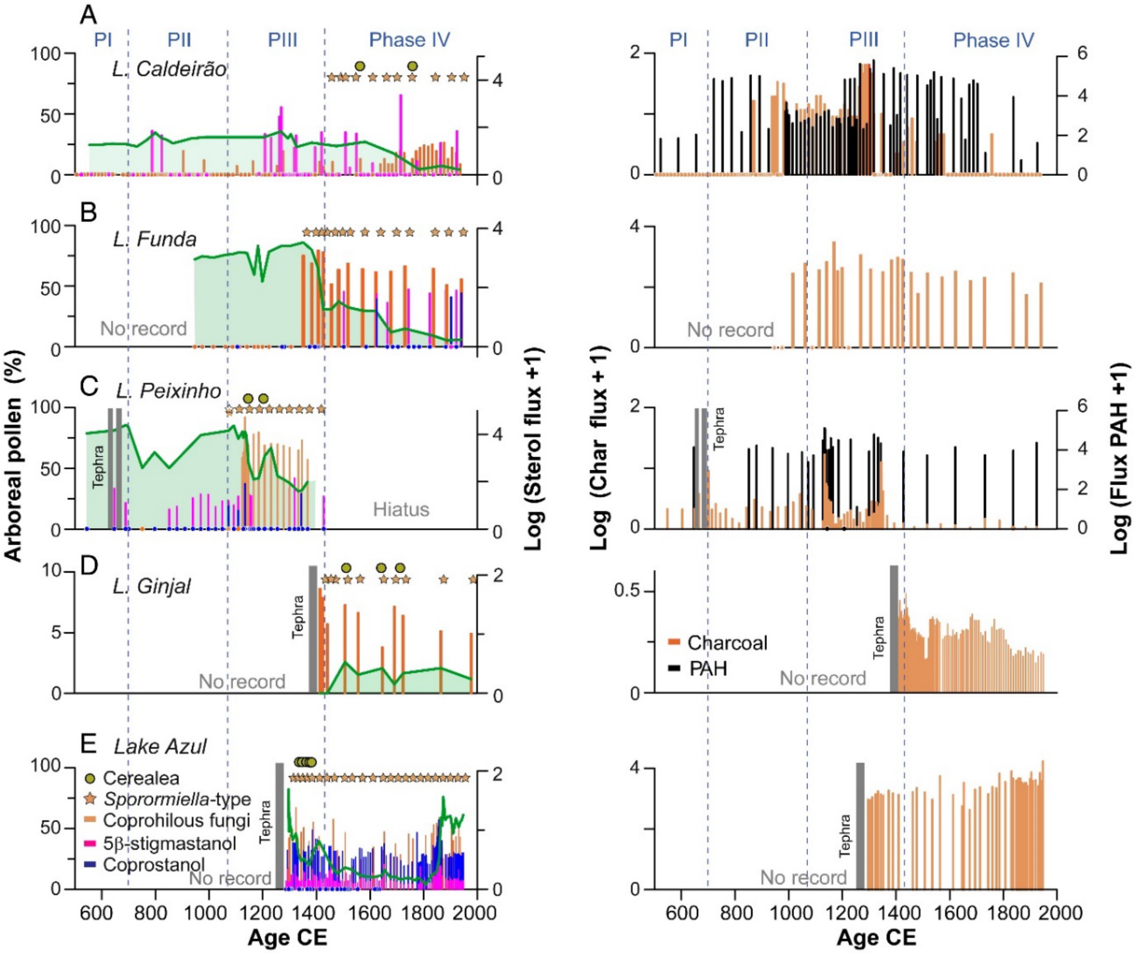
A
PI
PII
PIII
Phase IV
L. Caldeirão
B
L. Funda
No record
C
L. Peixinho
Tephra
Hiatus
D
L. Ginjal
E
Lake Azul
Cerealea
Sporormiella-type
Coprohilous fungi
5β-stigmastanol
Coprostanol
Charcoal
PAH
Arboreal pollen (%)
Log (Sterol flux +1)
Log (Char flux +1)
Log (Flux PAH +1)
Age CE
600 800 1000 1200 1400 1600 1800 2000

Figure 2.

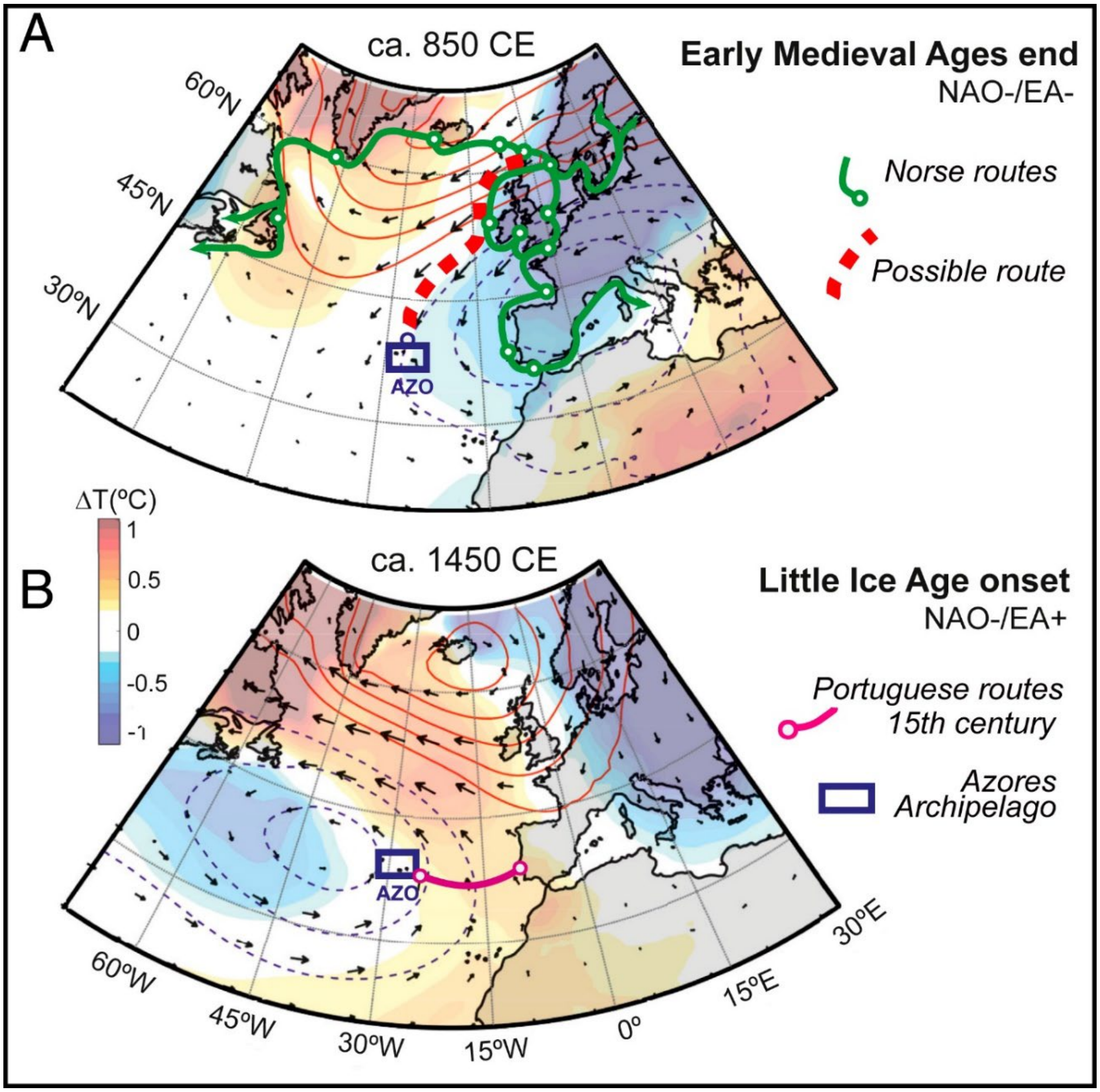
A
ca. 850 CE
Early Medieval Ages end
NAO-/EA-
Norse routes
Possible route
60ºN
45ºN
30ºN
AZO
ΔT(ºC)
1
0.5
0
-0.5
-1
B
ca. 1450 CE
Little Ice Age onset
NAO-/EA+
Portuguese routes
15th century
Azores
Archipelago
AZO
60ºW
45ºW
30ºW
15ºW
0º
15ºE
30ºE

Figure 3.

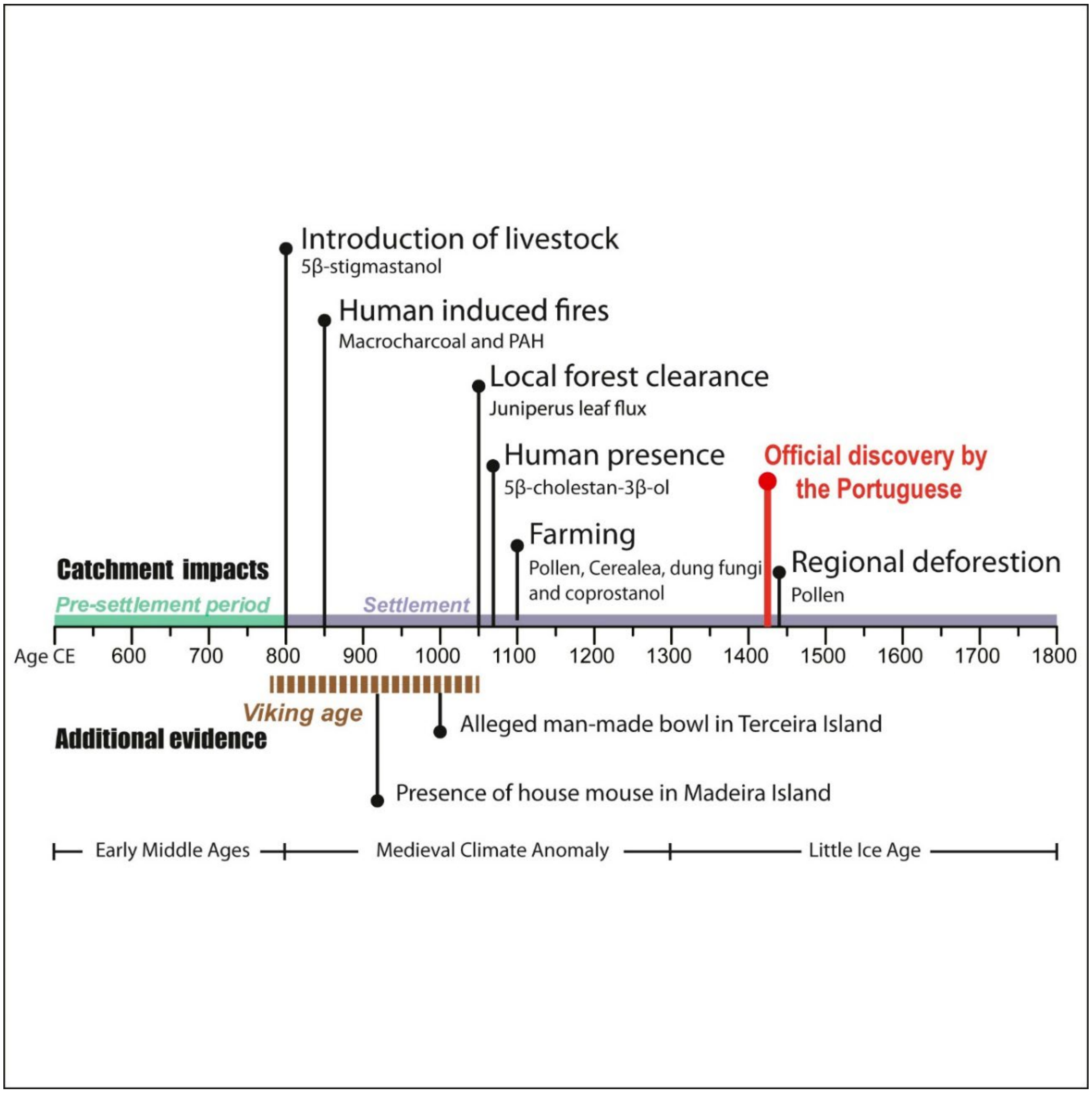
Introduction of livestock
5β-stigmastanol
Human induced fires
Macrocharcoal and PAH
Local forest clearance
Juniperus leaf flux
Human presence
5β-cholestan-3β-ol
Official discovery by the Portuguese
Farming
Pollen, Cerealea, dung fungi and coprostanol
Regional deforestion
Pollen
Catchment impacts
Pre-settlement period
Settlement
Age CE
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
Viking age
Alleged man-made bowl in Terceira Island
Additional evidence
Presence of house mouse in Madeira Island
Early Middle Ages
Medieval Climate Anomaly
Little Ice Age

Figure 4.