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Climate, biogeography, and human resilience in the demographic history of the Canary Islands during the Amazigh period

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This study explores the dynamic interplay between biogeography, climate variability, and human agency in shaping the population trajectories of Amazigh communities in the Canary Islands (1st to fifteenth centuries cal CE). Using radiocarbon dating as a proxy for population size, this research suggests potential links between demographic trends and environmental factors, highlighting how climatic phases influence agricultural productivity and settlement patterns. Favorable conditions during the Roman Warm Period (RWP) facilitated population expansion, whereas climatic stress during positive phases of the North Atlantic oscillation (NAO) (700–800 cal CE) led to significant demographic declines, particularly on smaller and more arid islands. Larger and ecologically more diverse islands, such as Gran Canaria and Tenerife, showed resilience due to their ecological diversity, agricultural innovations, and food security strategies, which supported sustained growth even during challenging periods such as the Early Medieval Climate Anomaly (MCA, 800–1150 cal CE). From 1150 to 1350 cal CE, cooler sea surface temperatures and a prevailing negative NAO phase increased marine productivity, enabling demographic recovery across islands. However, the arrival of Europeans in the fourteenth–fifteenth centuries introduced external disruptions, including slave raids, novel pathogens, and land seizures, leading to societal collapse. Overall, this study highlights the critical role of environmental diversity and agricultural adaptability in supporting human populations through climatic change and offers valuable perspectives on the relationships among climate, biogeography and human societies.

The climate during the late Holocene was characterized by remarkable stability, with annual global mean temperatures marked by less extreme variations. However, research shows pronounced changes in hydrological cycles, including changes in precipitation patterns, river flows and drought frequency, with varying impacts on different regions of the world[1]. Reconstructed temperature data suggest a combination of climate changes over the last two millennia driven by external factors and inherent natural variations due to orbital forcing, which could range from interannual to millennial timescales[2]. Spatial climate reconstructions emphasize the role of internal variability in defining the timing and intensity of temperature peaks over the last two millennia[3]. While broad temperature trends such as the "Roman Warm Period" (RWP, ca. 300 BCE–550 CE), the "Medieval Climate Anomaly" (MCA, ca. 800–1300CE) and the "Little Ice Age" (LIA, ca. 1300–1850 CE) can be identified, more localized climatic disturbances, such as the "North Atlantic Oscillation" (NAO)[4] and the "El Niño-Southern Oscillation" (ENSO)[5], play important roles in shaping human-environment interactions at local and regional scales during these periods[6–9].

The combination of detailed archaeological evidence with paleoclimate data from the late Holocene (ca. 4200 BP to present) can shed light on how rapidly climatic and environmental changes often led to social, political and cultural transformations in human societies[6,7,10,11]. An important finding is that there is a correlation between climate oscillations and long-term demographic trends[7,12]. The complex interaction between climate and human societies is particularly striking when examining historical populations of oceanic islands[13,14], as

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inherent isolation and limited ecological niches create unique conditions that shape human societies[15]. While the archaeological evidence confirms that the challenges posed by climatic variability led to significant social change, there is also compelling evidence of their resilience to these challenges through specific adaptations[13,16,17].

The Amazigh or Berber period in the Canary Islands (first–fifteenth century CE) is unique in that it provides an opportunity to study the dynamic relationship between demography and rapid climate fluctuations during the last two millennia of the late Holocene. The first settlers, Amazigh farming populations from western North Africa[18], encountered a series of environmentally diverse and pristine islands resulting from different orographic, meteorological and ecological factors (Fig. 1; Supplementary Note 1)[19]. The archipelago finally saw European sailors set foot on their shores in the late Middle Ages and were finally conquered by the Castilian kingdom in 1496[20]. Early European narratives describing indigenous Amazigh inhabitants reported remarkable heterogeneity across the archipelago in aspects such as social structure, material culture, subsistence strategies and population size[21–24]. This is supported by archaeological research, which shows that island communities have changed over time[23,25–27].

Archaeologists have explained this diversity by the effects of the following factors: (1) island size and its ecological constraints[28–31]; (2) ethnic diversity[32]; (3) progressive isolation subsequent to the initial settlement[24,33,34]; (4) new waves of human migration[25,35,36]; and (5) climatic fluctuations[23,37–39]. However, the precise ways in which these factors interacted over time and collectively shaped Amazigh communities remain unclear, underscoring the need for further research.

The present study adopted a multidimensional approach to delve deeper into the relationships among island biogeography, genetic diversity, climate oscillations and demographic trends during the Amazigh period of the Canary Islands (first–fifteenth centuries cal CE). This research considers the importance of multidisciplinary approaches for understanding how climatic and environmental variations have affected human societies over time[11]. The analysis resorted to Summed Probability Distribution (SPD) modeling of radiocarbon dates as proxies of population size[41] (see Methods and Supplementary Note 4). This approach is based on the premise that larger populations are likely to yield a greater number of cultural deposits, which in turn yield greater numbers of radiocarbon samples collected from archaeological sites (Fig. 2). The specific shape of the probability distributions of each radiocarbon date reflects both the measurement errors and the peculiarities of the calibration curve. The fluctuations observed among the calibrated distributions can be interpreted as indicating phases of demographic expansion and contraction, information that offers insight into historical demographic trends[42,43]. This approach has not been extensively developed in the Canary Islands to date.

Results

Demographic trends throughout the archipelago

An initial task of this study consisted of assembling a nonnormalized SPD of calibrated radiocarbon dates (n = 648) linked to the Archipelago's Amazigh period (Fig. 3; Fig. S1) that were previously filtered by the chronometric hygiene protocol (class 1 and 2 radiocarbon dates; see Methods). The analysis of the SPD reveals a stepped demographic trajectory throughout the Amazigh period, which aligns well with the raw counts of archaeological

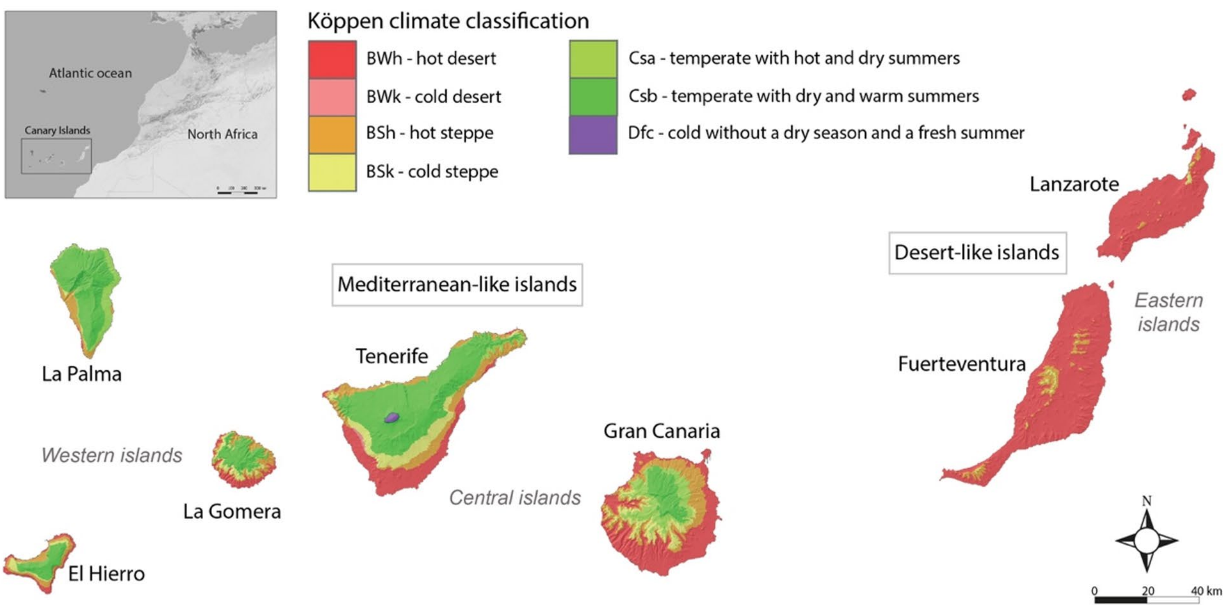

Fig. 1. Map of the Canary Islands according to the Köppen Climate Classification[40]. The upper left map shows the archipelago in relation to the African continent.

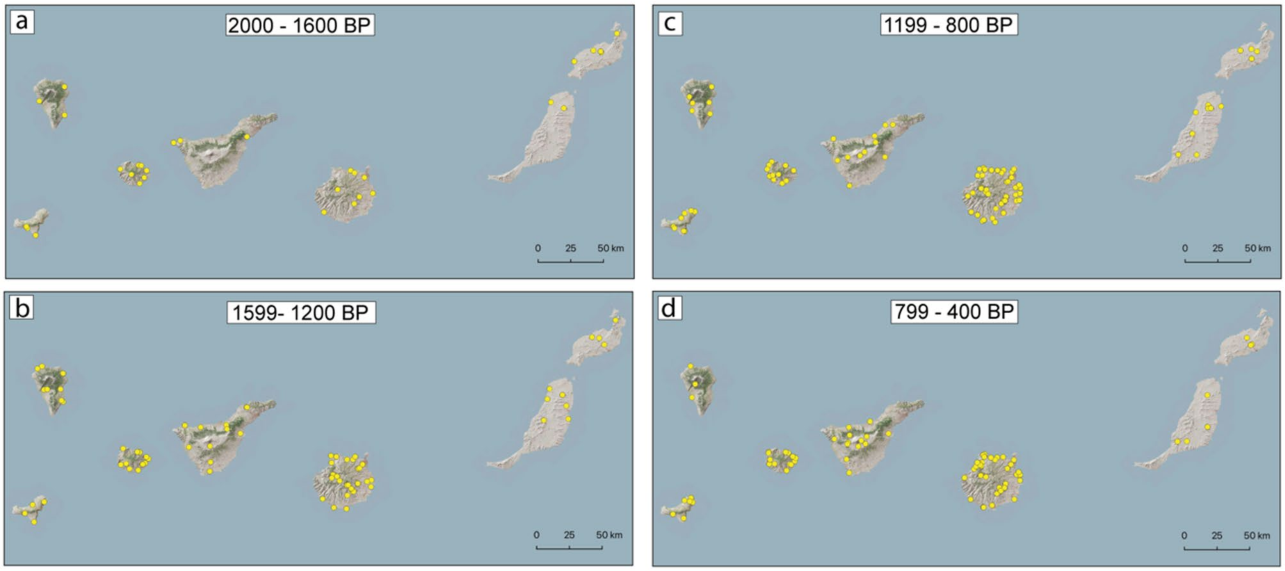

Fig. 2. Maps of the Canary Islands showing the distribution of archaeological sites from the Amazigh period, grouped into intervals of 400 years (uncalibrated BP). These maps illustrate fluctuations in the number of sites and the intensity of human occupation over time: (**a**) 2000–1600 BP; (**b**) 1599–1200 BP; (**c**) 1199–800 BP; (**d**) 799–400 BP.

sites and radiocarbon dates (Fig. 3d). Despite this overarching trend, there are periodic fluctuations. First, there was logistic population growth from the first major human colonization until approximately 700 cal CE. This growth was followed by a brief decline until 800 cal CE, which was succeeded by a minimal increase until 1150 cal CE. This was then supplanted by a second logistic demographic increase until 1350 cal CE. The SPD likewise reveals a demographic collapse between 1350 and 1500 cal CE (Fig. 3a). The raw data of the quantity of archaeological sites and radiocarbon data also revealed similar trends over time. However, the oscillations of the curves tend to undergo changes early on.

Island biogeography and demographic trends in the Canary Islands

SPDs were also used to characterize the potential differences in demographic trends between islands with desert-like climates and those with Mediterranean-like climates (Figs. 1 and 4). The nonnormalized SPDs and raw data on the number of archaeological sites and radiocarbon dates clearly reveal two distinct population dynamics during the Amazigh period (Fig. 4). Desert-like islands show minimal demographic growth during the initial centuries of archipelago colonization, with population levels remaining relatively stable until approximately 1150 cal CE. Following this period, the SPDs indicate a gradual demographic increase that persisted until approximately 1400 cal CE.

The Mediterranean-like islands, by contrast, are characterized by a steep population rise. This is initiated with logistic demographic growth from the outset of colonization up to approximately 700 cal CE, when a brief decline appears. A steady population dynamic clearly occurred between 750 and 1150 cal CE, followed by robust demographic expansion from 1150 to 1350 cal CE (Fig. 4). The SPDs for both desert-like and Mediterranean islands revealed a population decline starting at 1350 cal CE (Fig. 3). Notably, the demographic trends in the islands with Mediterranean-like climates are highly influenced by population fluctuations experienced by the central and larger islands of Gran Canaria and Tenerife (Fig. 4). Indeed, a detailed examination of the westernmost islands (La Gomera, La Palma and El Hierro) suggests a unique population dynamic that is remarkably varied compared with that of the central islands (Figs. 4d and 5).

Demographic trends of Islands with high and low genetic diversity

The SPD plots of radiocarbon dates on islands with different levels of human genetic diversity[47] revealed different demographic trajectories (Fig. 4). Populations on islands with relatively high genetic diversity, such as Gran Canaria, Tenerife, and La Palma, exhibited a stepped demographic pattern consistent with the overall trends observed for the archipelago. These patterns closely resemble those of islands with Mediterranean-like climates (Fig. 3). Notably, the data from Gran Canaria—comprising 56% of the study dataset (n = 364 of 648)—significantly influence this trend.

In contrast, islands with lower genetic diversity, including Lanzarote, Fuerteventura, La Gomera, and El Hierro, show markedly different population dynamics. Their populations show minimal demographic growth during the early centuries of colonization, persisting until approximately 1100 cal CE (Fig. 4d). This phase was followed by a sharp demographic increase between 1150 and 1350 cal CE, with notable intensification from 1200 to 1350 cal CE. These patterns align closely with raw archaeological site counts and radiocarbon dating trends (Fig. 4e).

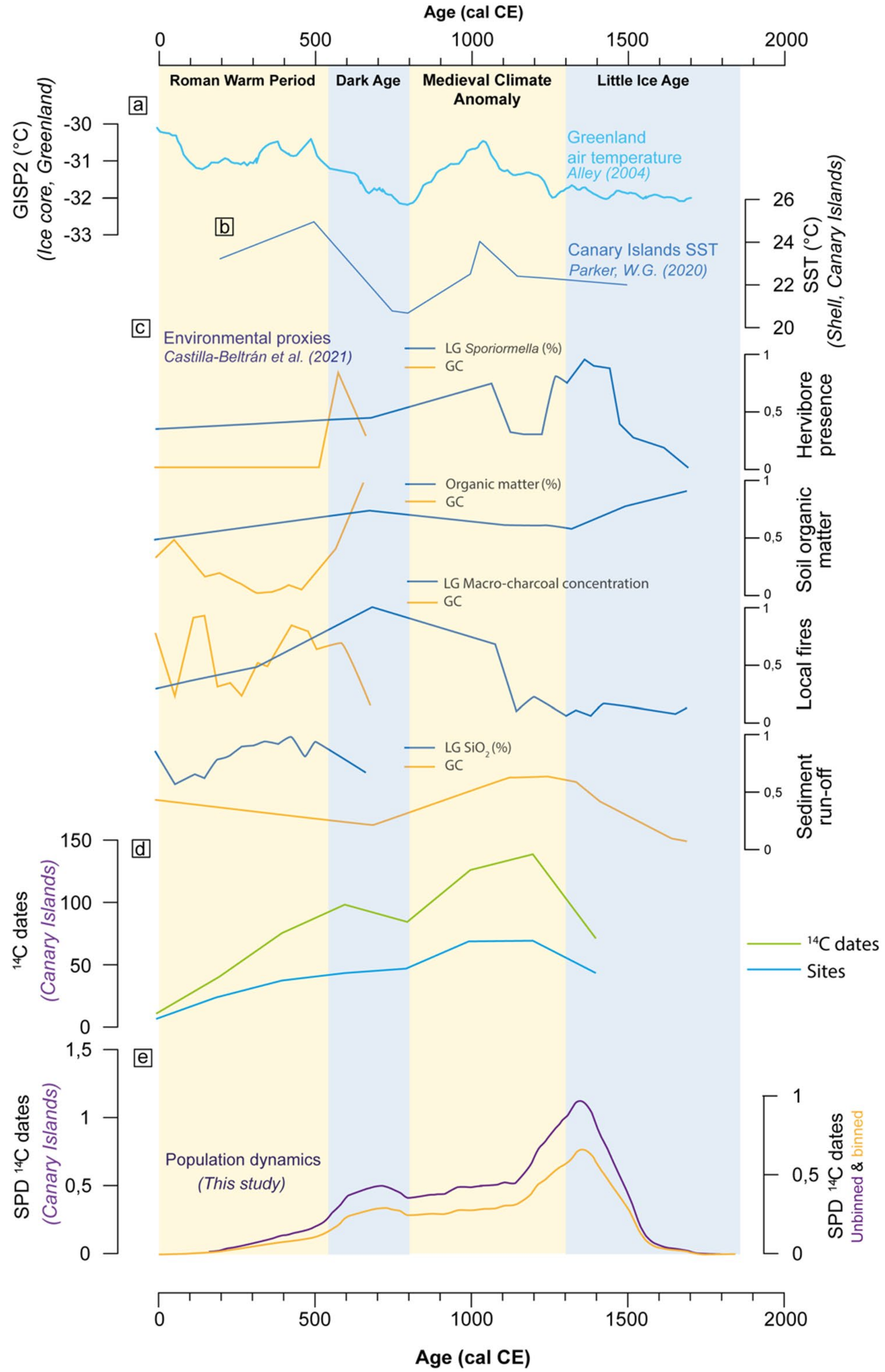

Fig. 3. Climate, environmental and radiocarbon data from the Canary Islands. (**a**) Reconstructed air temperatures from GISP2 ice cores[44]; (**b**) reconstructed surface sea temperatures (SSTs) from $\delta^{18}O$ values of the margins of archaeological *Patella candei* shells from the Canary Islands[45]; (**c**) time series of different environmental proxies normalized from 0 to 1 derived from core samples from the Islands of La Gomera (LG) and Gran Canaria (GC)[46]; (**d**) number of archaeological sites and radiocarbon dates in 200-y intervals (Table S3); (**e**) SPDs of radiocarbon dates from the Canarian archipelago (200-y moving average). The violet line represents the calibrated unbinned radiocarbon dates, whereas the orange line corresponds to the radiocarbon dates grouped into 50-y bins; yellow shaded areas highlight warmer periods (the Roman Warm Period and the Medieval climate oscillation).

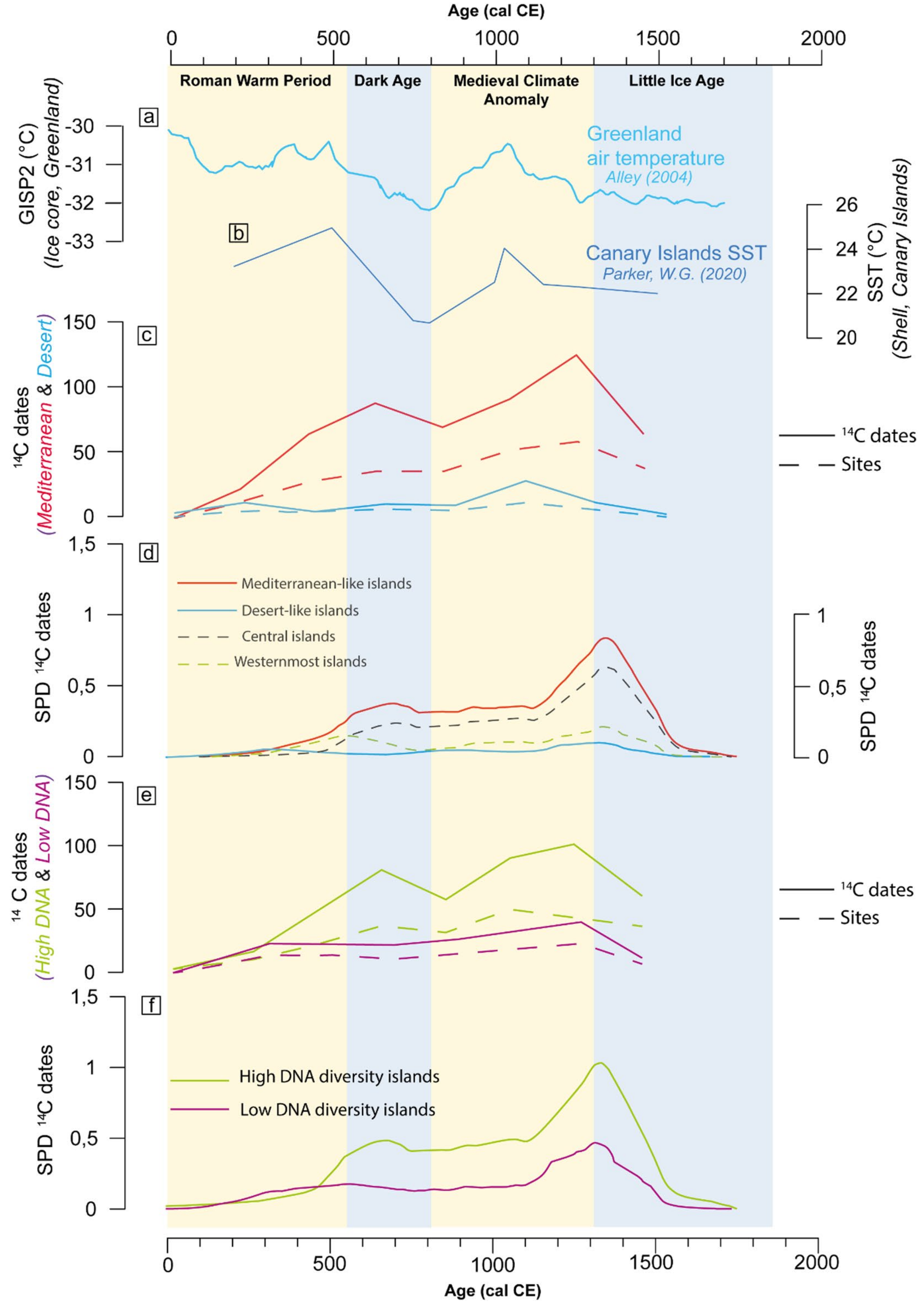

Fig. 4. SPDs of radiocarbon dates of the desert-like and Mediterranean-like islands and islands with high and low DNA diversity compared with selected climate records: (**a**) reconstructed air temperatures from the GISP2 ice cores[44]; (**b**) reconstructed surface temperature (SST) from $\delta^{18}O$ values of the margin archaeological *Patella candei* shells from the Canary Islands[45]; (**c**) number of archaeological sites and radiocarbon dates in 200-y intervals from desert-like and Mediterranean-like islands (Supplementary Tables S4–S5); (**d**) SPDs representing desert-like and Mediterranean-like islands. The central and western islands are included for comparative purposes. (**e**) Number of archaeological sites and radiocarbon dates in 200-y intervals from low DNA and high DNA diversity[47] (Supplementary Tables S6 and S7). (**f**) SPDs of radiocarbon dates from islands marked by high and low human DNA genetic diversity serve as proxies of population dynamics. The radiocarbon dates are grouped into 50-y bins, and the SPDs are smoothed by a 200-y moving average.

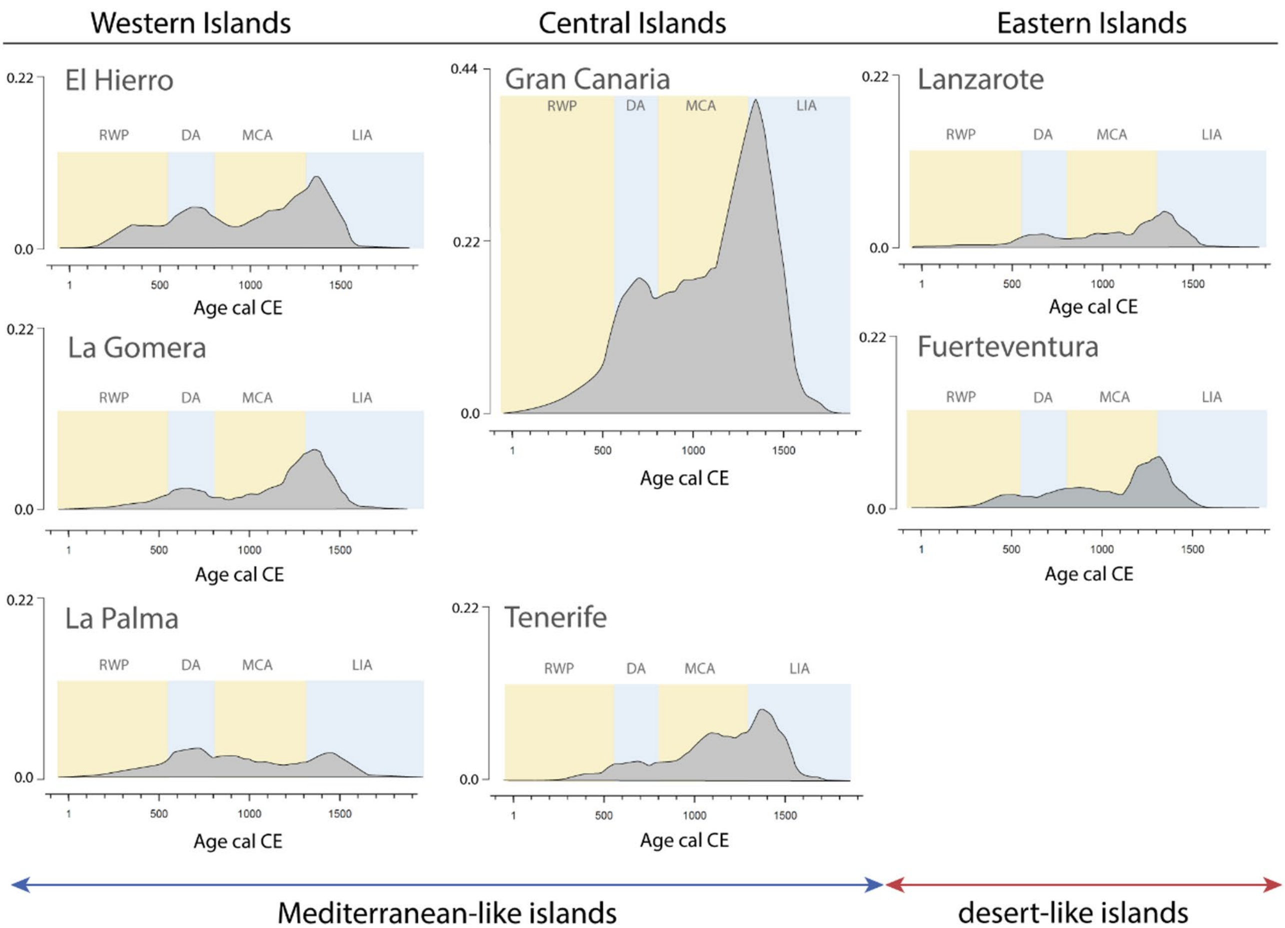

Fig. 5. Summed probability densities (SPDs) of the radiocarbon dates of each of the seven islands of the Canarian archipelago serving as proxies of ancient demographic dynamics. The data are grouped into 50-y bins, and the SPDs are smoothed by resorting to a 200-y moving average.

Island-specific demographic trends

The results suggest that the large volume of data from Gran Canaria significantly influenced analyses involving this island, particularly within the context of Mediterranean-like climates or islands with high genetic diversity. This underscores the importance of evaluating the demographic dynamics of each island individually to discern their unique trajectories. The SPDs for each island confirmed distinct population dynamics (Fig. 5). Overall, the SPD plots reveal a pattern of logistic demographic growth—albeit with interisland variability—from the beginning of colonization until approximately 550–750 cal CE (Fig. 5). This phase was followed by varying degrees of demographic decline across the islands. These declines were relatively mild in Fuerteventura, Lanzarote, Gran Canaria, and Tenerife, but more pronounced "overshoot" scenarios were evident in La Gomera and El Hierro. The subsequent phases also highlighted significant differences across the archipelago. For example, La Palma maintained a stable demographic pattern, with only a modest population increase between 1200 and 1450 cal CE, suggesting persistently low population densities throughout the Amazigh period. Lanzarote and Fuerteventura displayed similar trajectories, characterized by noticeable population spikes between 1100 and 1350 cal CE. In contrast, La Gomera and El Hierro experienced a pronounced population downturn between 700 and 900 cal CE, followed by a logistic demographic resurgence extending to 1350 cal CE. Gran Canaria and Tenerife exhibited stepped trajectories, marked by substantial population expansions between 1100 and 1400 cal CE. Notably, Tenerife experienced a brief population fluctuation at approximately 1150–1250 cal CE.

Discussion

Population dynamics during initial colonization

The Amazigh colonization of the Canary Islands between the first and third centuries CE[18], coincided with Roman expansion in northwestern Africa, alongside a period of more humid winters and cooler summers at approximately 200 cal CE[48–52]. The earliest human presence on the islands dates to a short-term settlement on Lobos islet (2 km off the coast of Fuerteventura)(Fig. S2), spanning the first century BCE to the first century CE. However, evidence indicates that Amazigh settlers arrived on Lanzarote between the first and third centuries CE and formed the indigenous communities later encountered by European seafarers in the late medieval period[18]. Within 200 years, the Amazigh settlers spread throughout the archipelago, with the westernmost islands settling around the same time as the easternmost islands. This study supports these findings, showing that Amazigh communities maintained robust demographic growth, facilitating their successful colonization and expansion across the Canary Islands.

Archaeological research has demonstrated how Amazigh populations transformed islands into domestic landscapes through crop cultivation and livestock husbandry[22,28,29,53]. It is important to emphasize, however, that the archipelago offered few edible native terrestrial resources, particularly owing to the absence of medium-sized to large mammals[28,29,54]. Despite these constraints, the island populations successfully created sustainable environments that facilitated long-term settlement and supported demographic growth, as evidenced by this study. These findings align with broader patterns observed among farming communities that colonized pristine or minimally modified environments, such as the Neolithic expansion into Europe[55] and the initial settlement of other unspoiled oceanic islands[56,57].

Island environments shaped demographics

The data show clear demographic differences between the trends observed on desert-like and Mediterranean-like climate-bearing islands (Figs. 3 and 4). Desert-like islands display minimal demographic growth during the initial centuries of archipelago colonization, which contrasts with the stepped growth trajectory characteristic of Mediterranean-like islands. Interestingly, the population growth on Mediterranean-like islands coincides with a demographic decline on desert-like islands. The earlier onset of population growth on desert-like islands can be attributed to their earlier colonization[18]. This synchronicity suggests that the SPDs reflect migratory trends from the easternmost islands to the central and westernmost islands. This pattern aligns with the spread of barley throughout the archipelago, as revealed by genomic analyses[34]. However, minimal demographic growth was also observed during the early centuries of colonization on islands with low genetic diversity, regardless of their classification as desert-like (e.g., Lanzarote and Fuerteventura) or Mediterranean-like (e.g., La Gomera and El Hierro). The small size of La Gomera and El Hierro likely posed significant constraints on demographic development (Fig. 1; Table 1). Furthermore, genetic data suggest that small founding populations were present at the onset of colonization on these islands[47], limiting their potential for sustained population growth over time.

The logistic population growth observed from the onset of human colonization persisted until approximately 700 cal CE (Figs. 3 and 6). This demographic trend resembles the "boom-and-bust" dynamics observed during the European Neolithic, where an initial population surge persisted until the carrying capacity of newly settled territories was reached, ultimately triggering a decline[55]. A similar pattern has been documented in the early demographic developments of farming communities in other island settings[56,60]. What remains particularly intriguing, however, is how Amazigh populations across diverse islands appear to have reached their respective carrying capacities around the same time, despite the significant differences in island size and ecological constraints (Figs. 4 and 6). These disparities include pronounced contrasts between Mediterranean-like and desert-like islands, which would have likely shaped their demographic trajectories in distinct ways. Thus, the carrying capacity of the islands alone does not fully account for the population dynamics observed in this study. Climatic factors, among other influences, may have also shaped the demographic trends of the Amazigh populations.

Climate change and demographic growth

The population growth notably accelerated between 500 and 700 cal CE (Figs. 3 and 6). This period coincides with the transition from the Roman Warm Period (RWP) to the Dark-age cold period (DACP). The DACP was characterized by cooler temperatures, winter cooling and persistent summer droughts, punctuated by occasional wet summers in the North Atlantic[61,62]. This climatic scenario was regulated by a dominant negative North Atlantic Oscillation (NAO) climatic phase, which strongly influenced the moist trade winds and the Canary Current (Fig. 6)[58,63]. Negative NAO phases are characterized by a weakening of the Azores High and a southward shift in Atlantic storm tracks, which have notable implications for the Canary Islands[64]. During negative NAO phases, approximately 80% of the yearly rainfall occurs between November and March, typically accompanied by elevated atmospheric moisture and warmer temperatures. Conversely, positive NAO phases, such as those in the RWP, are associated with increased aridity and cooler temperatures[58].

The negative NAO conditions during the DACP overlapped with the onset of the Atlantic Ice Rafting Event (Bond Event 1), marked by a southerly shift in the westerly wind belt, variable but overall drier conditions in North Africa[51] and cooling of the Atlantic median sea surface temperature (SST), as evidenced by data gleaned

	Lanzarote	Fuerteventura	Gran Canaria	Tenerife	La Gomera	La Palma	El Hierro
Area (km^2)	846	1633	1530	2034	370	708	269
Maximum elevation (m.a.s.l.)	671	807	1956	3715	1487	2423	1501
Initial human colonization (cal. CE)[1]	70–240	270–525	490–530	155–485	275–405	245–430	170–330
Climate type[2]	Desert	Desert	Mediterranean	Mediterranean	Mediterranean	Mediterranean	Mediterranean
Precipitation (mm)[3]	157	120	300	425	370	740	353
Current population[4]	158.798	124.152	862.893	948.815	22.361	84.338	11.659

Table 1. Summary of the geographical, historical and demographic data of each island of the Canarian archipelago. [1]Modeled estimates of initial colonization using Bayesian analysis of radiocarbon dates (95.4%)[18]. [2]Based on the Köppen Climate Classification of the Canary Islands[40] (Fig. 1). [3]Plan Hidrológico de Canarias. [4]Instituto Nacional de Estadística, year 2023.

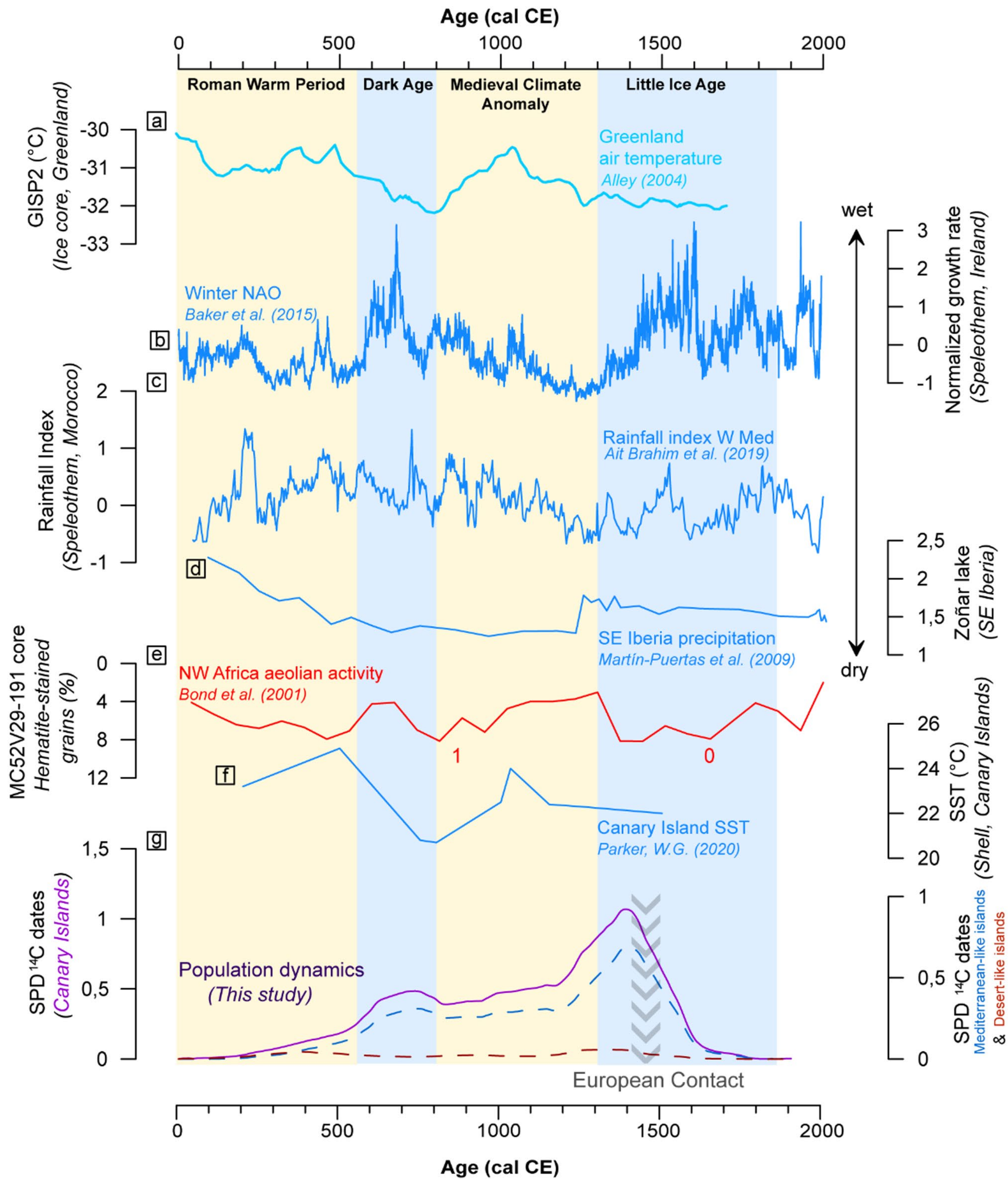

Fig. 6. Paleoclimate proxies and Canarian population dynamics. (**a**) Reconstructed air temperatures from GISP2 ice cores[44]; (**b**) reconstruction of the winter NAO on the basis of growth rates of Irish speleothems[58]; (**c**) reconstructed speleothem-based precipitation variability in Morocco[51]; (**d**) lake-level reconstruction for Lake Zoñar (southern Iberia)[52]; and (**d**) hematite-stained grain percentage (%) from core MC52V29-191 in the Atlantic Ocean[59]. The numbers refer to IRD or Bond events; (**f**) reconstructed surface sea temperature (SST) from $\delta^{18}O$ values of the margin of archaeological *Patella candei* shells from the Canary Islands[45]; (**g**) SPD of radiocarbon dates from the Canarian archipelago serving as a proxy for population dynamics. The violet line represents calibrated radiocarbon dates grouped into 200-y bins. The yellow shaded areas represent the Roman Warm Period and the Medieval climate oscillation, whereas the blue shaded areas represent the main Canarian population growth intervals during humid periods under negative NAO conditions. The gray downward arrows highlight the European arrival.

Climate proxy	Total	Onset—700 cal CE	750–1150 cal CE	1150–1350 cal CE
GISP2	***−0.52 (p = 0.00)***	***−0.75 (p = 0.00)***	−0.15 (*p* = 0.68)	−0.31 (*p* = 0.61)
NAO index	***0.87 (p = 0.00)***	***0.89 (p = 0.00)***	0.33 (*p* = 0.14)	***0.65 (p = 0.03)***
Rainfall index Morocco	−0.31 (*p* = 0.11)	−0.01 (*p* = 0.96)	−0.24 (*p* = 0.53)	***0.66 (p = 0.03)***

Table 2. Pearson correlation of the SPD and different climate proxies for Mediterranean-like islands across various temporal resolutions. Significant values are in [bold and italics].

Climate proxy	Total	Onset—1150 cal CE	1150–1400 cal CE
GISP2	−0.34 (*p* = 0.08)	−0.12 (*p* = 0.59)	−0.11 (*p* = 0.75)
NAO index	***0.54 (p = 0.00)***	***0.45 (p = 0.03)***	−0.50 (*p* = 0.11)
Rainfall index Morocco	0.13 (*p* = 0.51)	0.14 (*p* = 0.51)	0.02 (*p* = 0.95)

Table 3. Pearson correlation coefficients of the SPD and different climate proxies for desert islands across various temporal resolutions. Significant values are in [bold and italics].

from archaeological shells collected in archaeological Canarian shell middens (Fig. 6)[45]. This trend is similarly reflected in the SPD curves as well as in the raw counts of archaeological sites and radiocarbon dates (Figs. 3, 4 and 6). The additional winter rainfall during negative NAO phases would have increased soil moisture, potentially benefiting rain-fed crops such as barley and wheat. This could have allowed for more reliable yields and even the cultivation of marginal lands that might otherwise have been too dry. Cooler temperatures could have benefited livestock by reducing heat stress and increasing the availability of forage due to increased plant growth. However, the variability associated with negative NAO conditions—such as sudden changes in rainfall intensity[65]—might have posed challenges for Amazigh populations.

To examine the relationship between SPD curves and the Winter NAO Index[58], both datasets were interpolated onto an annual timescale via linear interpolation, ensuring comparability. The analysis was conducted for the entire indigenous occupation period, as well as separately for each phase of demographic change on both desert-like and Mediterranean-type islands (Tables 2 and 3). For Mediterranean-type islands, the correlation between the SPD curve and the winter NAO index[58] is strong and statistically significant across the entire analyzed period (0–1400 cal CE; $r = 0.87$, $p < 0.01$) and during the initial population growth phase (0–1150 cal CE; $r = 0.89$, $p < 0.01$) (Table 2). This indicates a close association between humid (negative) NAO phases and periods of increased human occupation. The correlation weakens and becomes nonsignificant during intermediate periods ($r = 0.33$, $p = 0.14$) (Table 2), but it strengthens again during the second population boom (1150–1350 cal CE; $r = 0.65$, $p = 0.03$) (Table 2). A similar pattern is observed during this later period with the Morocco Rainfall Index[51], which shows a moderately strong and significant correlation ($r = 0.66$, $p = 0.03$) (Table 2).

For desert islands, the SPD curve and winter NAO index[58] also exhibited a significant positive correlation across the entire period (0–1400 cal CE; $r = 0.54$, $p < 0.01$) and during the first demographic phase (0–1150 cal CE; $r = 0.45$, $p = 0.03$) (Table 3). This suggests that negative NAO phases improved living conditions on desert islands. Between 1150 and 1400 cal CE, the correlation reversed to negative ($r = -0.50$, $p = 0.11$) (Table 3), although it was not statistically significant, possibly indicating a shift in climate-population interactions. This reversal might reflect the climate resilience of desert islands, as their flat terrain and low elevation limit rainfall increases during wetter (negative NAO) phases, reducing potential impacts.

Importantly, negative NAO conditions contribute to increased weather variability across islands[64]. While these phases generally result in above-average rainfall, the specific impacts can differ significantly depending on the local topography and prevailing wind patterns. The effects of negative NAO conditions likely varied between islands owing to differences in topography and microclimates[64]. As observed in the correlation analysis, islands with higher elevations, such as Tenerife and La Palma, might have benefited more from increased rainfall due to orographic effects, whereas lower, desert-like islands, such as Lanzarote and Fuerteventura, may have experienced only marginal improvements. These disparities would have required island populations to adapt their subsistence strategies to local conditions, such as focusing more on drought-resistant crops or relying heavily on livestock in arid areas.

Demographic uncertainty and stabilization

Our findings reveal a shift in the population dynamics of the archipelago, characterized by a decline from around 700 to 800 cal CE (Figs. 3 and 6). Notably, this trend began earlier—approximately 600 cal CE—among island populations with low genetic variability (Fig. 4). Variations can be distinctly observed when island-by-island analysis is performed with all, except for the central islands, revealing a pronounced cutback at the same time (Fig. 5). This shift coincides with the onset of predominantly dominant positive NAO conditions at approximately 750 cal CE, leading to consistent warming and a reduction in the precipitation index across western North Africa and Iberia (Fig. 6b–e)[2,7,9,51,66–68].

Pollen records, lake evolution and isotopic analyses of speleothems carried out in the Iberian Peninsula and northwestern North Africa suggest periods of drought during the late 7th and early eighth centuries CE[69,70]. Paleoclimatic records from these areas also reveal a significant episode of cooling around 750 cal CE[50,63]. Moreover, the central Sahara underwent pronounced episodes of aridification from 550 to 750 CE[71]. Consequently, the onset of dominant positive NAO conditions at approximately 750 cal CE, together with decreased precipitation, likely had profound impacts on Amazigh subsistence strategies in the Canary Islands and, subsequently, on the population dynamics of the island populations.

The data collected in our study suggest that the entire archipelago experienced only a minimal increase in population size during most of the Medieval Climate Anomaly (MCA), between 800 and 1150 cal CE (Fig. 3). Moreover, paleoclimate records from western North Africa indicate that the MCA was generally characterized by drier conditions, likely linked to a predominantly positive phase of the North Atlantic Oscillation (Fig. 6b)[2,58,63]. This period is characterized by considerable variability in rainfall in Morocco and the Iberian Peninsula. The data from western North Africa indicate an overall drying trend during the MCA, with more intense arid phases at approximately 940 and 1050 cal CE[72,73]. These drier conditions coincided with warmer average air temperatures inferred from GISP2 ice core data in Greenland (Figs. 3a and 6a). However, local records from Lake Sidi Ali and the Ait Ichou Swamp in Morocco document a short-lived cold episode between 1000 and 1050 CE—coinciding with the Oort solar minimum—underscoring the importance of regional and temporal climate variability within the broader MCA[2].

Elevated median sea surface temperatures (SSTs), reconstructed from $\delta^{18}O$ values in *Patella* sp. shells dated to 700–1200 cal CE at Amazigh sites in the Canary Islands, confirm this warming trend[45] (Figs. 3b and 6f). Similar findings are supported by stable isotope data from planktonic foraminifera off Cap Blanc, Mauritania[49,59], and observations of warmer, drier conditions in the Azores during the same period[74]. Multiproxy analyses of marine sediment cores from the Souss Valley (southwestern Morocco) and near the Canary Islands further suggest arid conditions linked to intensified northeasterly trade winds between 750 and 950 CE[75].

Proxies of environmental change proxies in Canarian archaeology

Wood charcoal analyses from archaeological sites across various islands have revealed significant arboreal changes over time[76–78]. Analyses of these materials in Fuerteventura at the cave of Villaverde (Fig. S2) from the 3rd to 7th CE reveal several tree species not currently known on the island, notably, Canarian laurel *(Laurus novocanariensis*) and the Canarian strawberry tree (*Arbutus canariensis*)[77]. However, these arboreal taxa disappeared from levels dating from the ninth century CE onward. Today, these species are known only to occur in the forests of Mediterranean-like islands and are absent in Fuerteventura. Analyses of charcoal remaining from archaeological sites also indicated a shift from tree species to shrubs starting at approximately the ninth century CE in Fuerteventura[77]. Paleoecological proxies from Mediterranean islands also reflect disturbances resulting from a decrease in local fires, a greater presence of herbivores and more sediment run-off[46] (Fig. 3). These changes in arboreal composition, along with the extinction of animals and soil erosion, are interpreted primarily as a result of anthropogenic activities during the transition to drier conditions and an arid climate during the MCA[28,29,76].

Analyses of SPDs from individual islands reveal distinct population trends during the MCA. On the desert-like islands of Fuerteventura, a decline occurred at approximately 900 cal CE, whereas on the westernmost islands (La Gomera, El Hierro, and La Palma), declines began at the beginning of the MCA (750–850 cal CE) (Fig. 5). Tenerife and Gran Canaria, in turn, experienced a demographic increase at the same time, provoking population expansion in the SPD of the whole archipelago and the Mediterranean-like islands (Figs. 3 and 4). Tenerife, the largest of the islands, reveals similar rainfall patterns to many of the other Mediterranean-like islands[40], and Gran Canaria, the third-largest island, shares biogeographic conditions with Tenerife (Fig. 1), indicating that the two islands share close environmental parallels. These observations suggest that the different demographic trends in the Canary Islands have probably been influenced by the size and biogeographical diversity of the islands (Fig. 1, Table 1), with the central islands offering a greater carrying capacity for human populations.

The carrying capacity of the Amazigh populations depended on the development of agriculture given the limited terrestrial food resources of the Canary Islands. Archaeobotanical research has shown that agriculture was practiced on all the islands from the first millennium CE until the arrival of Europeans in the Middle Ages[23]. Nonetheless, evidence suggests that crop diversity decreased over time in La Palma, Fuerteventura, La Gomera and El Hierro[23]—there is regrettably insufficient evidence to determine crop diversity fluctuations over time for Lanzarote. In contrast, archaeobotanical research has demonstrated that crop diversity has remained stable over time in Gran Canaria[23]. Oral conditions, odontometrics, and stable isotope analyses of humans bones also point to the significant role of agriculture in the diets of Tenerife and Gran Canaria populations[30,31,79–81]. Notably, historical written sources also highlight that Tenerife and Gran Canaria had the largest populations at the time of European arrival in the Middle Ages[82]. Therefore, the low diversity or absence of staple crops and their potential impact on food resources and security may have had a significant influence on their demographic trends.

A similar pattern of societal adaptation and vulnerability to climatic stress during the MCA (c. 800–1300 CE) is observed elsewhere in the western Mediterranean and North Africa. In Al-Andalus (Iberia under Islamic rule), historical records describe severe drought episodes (814–822, 867–874 CE) that led to crop failure and famine[83]. However, Al-Andalus displayed notable adaptive strategies through a "medieval green agricultural revolution," introducing new crops and advanced irrigation techniques such as water wheels and canals, thereby increasing resilience in semiarid environments[84]. These innovations supported demographic growth and urbanization despite climate stress. In the Maghreb, prolonged drought periods, particularly between the late 11th and middle twelfth centuries, severely impacted agricultural stability. However, the oasis city of Sijilmasa in Morocco exemplifies local adaptation to these challenges; following severe disruptions in the eleventh century due to warming and drying, Almoravid rulers diverted the Ziz River in 1055 CE, revitalizing agriculture and spurring economic recovery despite ongoing drought[85]. In the Eastern Mediterranean, climatic fluctuations notably affected Byzantine agriculture, impacting crucial crops such as wheat and vines. Although the Byzantines adapted through crop diversification, trade expansion, and social restructuring, some extreme climatic events intensified existing conflicts, negatively influencing political stability[86].

Our findings also highlight and confirm previous observations of a distinct demographic pattern in Gran Canaria[87]. This demographic trend may be related to the growing role of agriculture and irrigation systems and the development of large storage facilities during the MCA[23]. In fact, the presence of many cave granaries designed for the long-term storage of plant foods in Gran Canaria since the sixth century CE underlines the vital role of agricultural production on this island[23]. Importantly, genetic analyses suggest the presence of a larger population of barley grain in Gran Canaria during the seventh–eighth centuries CE, in contrast to the smaller population size of the latter period spanning the tenth–fourteenth centuries CE[34]. This change in population size may indicate that the warmer conditions of the MCA also affected Gran Canaria's agricultural system. A reduction in the barley cultivation scale coinciding with an increase in the size of the human population also suggests that other sources of food increased in importance during the MCA.

Another explanation may be that the size of their populations, after the decline from approximately 700 to 800 cal BC, did not facilitate demographic growth during this period. Paleogenomic analyses from El Hierro, La Gomera, Lanzarote, and Fuerteventura revealed evidence of reduced effective population sizes prior to the 10th to twelfth centuries CE[35,47]. The genetic diversity of these islands further reflects the effects of genetic drift and limited gene flow, with specific lineages becoming fixed or partially fixed over time. In particular, a pronounced genetic bottleneck was identified on El Hierro around the ninth century, which significantly reduced its population[47]. Individuals from this island exhibit elevated levels of consanguinity, likely driven by a combination of small effective population size, bottleneck events, and geographic isolation[47]. This is consistent with skeletal remains from El Hierro that display congenital disorders such as Klippel–Feil syndrome and spina bifida, which are indicative of inbreeding[88]. Interestingly, the SPD for El Hierro shows a sharp population decline between 600 and 800 cal CE, suggesting a significant demographic reduction during this period, which is consistent with the identified genetic bottleneck.

Strong demographic expansion during the MCA

The population dynamics of the archipelago underwent a pronounced increase between ca. 1150 and 1350 cal CE during the last phase of the MCA (Figs. 3 and 6). Notably, both desert-like and Mediterranean-like islands experienced significant population growth during this period (Fig. 3). Additionally, the SPDs also revealed population growth after 1150 cal CE on islands with both high and low genetic diversity (Fig. 4). In fact, a strong demographic surge can be observed when island-by-island analysis is performed (Fig. 5).

This demographic trend may be related to significant cooling of the sea surface temperature (SST) in the Canary Islands from 1000 to 1500 cal CE compared with both the beginning of the MCA and modern times (Fig. 6)[2,45,80]. This cooling trend is linked to the consolidation of the Canary Current upwelling zone adjacent to the Canary Islands, which brought currents of cooler, nutrient-rich water to the islands[89]. Seawater cooling is also recorded in marine cores GeoB6008 and OC437-7 around the same time, which reflects intensified upwelling in the Canary Current upwelling system rather than a wider regional climatic response[63]. Therefore, the local populations of coastal areas may have been able to exploit more marine resources[80]. Archaeological evidence supports the idea of greater exploitation of marine resources in Tenerife and Gran Canaria during this period[37,89–91]. It is also compelling that individuals from Gran Canaria's coastal regions suffer from auricular exostosis, a bone anomaly interpreted to have been caused by routine activities related to exploiting marine resources[37]. Taken together, these results suggest that a greater availability of marine resources may also have contributed to the demographic increase from 1150 to 1350 cal CE.

The marked increase in the population of Gran Canaria during the late phase of the MCA had a significant effect on the demographic trajectory of the entire archipelago (Figs. 3 and 5). Velasco et al.[87] hypothesized that this increase was due to the arrival of new populations from the African continent, accompanied by a wave of innovation. However, the study by Serrano et al.[47] found no genetic evidence suggesting an admixture event involving new human populations from the African continent. Preliminary analyses have also revealed no evidence of such admixture in the genetic makeup of domesticated plants or animals[34,92]. Archaeobotanical and zooarchaeological evidence further supports this conclusion, suggesting that the original "package" of domesticated plants and animals introduced during the initial colonization remained unchanged throughout the Amazigh period[23,29]. Moreover, similar demographic trends observed throughout the archipelago during the same period suggest that other factors, such as climatic amelioration, may have contributed to the population growth in Gran Canaria.

A plausible explanation for the unique development of Gran Canaria is the robust development of its agriculture[23]. Archaeological and genetic evidence indicates that the agriculture of Gran Canaria is extensive, diverse and resilient compared with that of the other islands[23,34]. This agricultural preeminence is reflected in the emphasis on food storage, as evidenced by the proliferation of fortified granaries—both in number and size—after the eleventh century cal CE[23,53,93]. Notably, such granaries are absent on Tenerife and the other islands of the archipelago. Their construction required considerable time and resources.

The last part of the archipelago's demographic growth coincides with an intense, negative NAO phase from 1300 to 1600 CE linked to a major reorganization of atmospheric and oceanic circulation in the North Atlantic (Fig. 6)[45,64,80] as during the first phase of demographic growth in the Canary Islands (Figs. 3 and 6). Speleothem records from Morocco also highlight a noticeable humid period flanked by relatively dry phases at the onset of the fourteenth century (Fig. 6)[51]. Palaeoecological analyses of five sediment cores from Gran Canaria, Tenerife, La Gomera, and La Palma revealed that environmental changes coincided with the last phase of the MCA (Fig. 3)[46]. Samples from the islands of La Palma and Tenerife also show an increase in the collection of wood from trees requiring higher humidity, especially between the 12th and 15th cal CE[76,78]. Paleorecords from western North Africa indicate a cooling trend from 1300 CE, which may be a delayed response to the solar Wolf Minimum and/

or the decline in the NAO and Atlantic multidecadal oscillation (AMO)[2]. Notably, a study by Zhao et al.[75] of two marine sediment cores collected off the southwest coast of Morocco and the Canary Islands revealed an increase in riverine inputs after 950 CE, most likely due to a combination of increased rainfall and human activity. This period also coincides with the onset of the Little Ice Age, a climatic episode that led to cooler temperatures and possibly an increase in rainfall and lower rates of evapotranspiration, which yielded more terrestrial food resources and/or food security for the island populations[7].

The results of our study also suggest that El Hierro's demographic trend mirrors that of the islands with greater genetic diversity, despite the bottleneck effect experienced by its population (Figs. 4 and 5). Genetic bottlenecks can increase the frequency of deleterious mutations, which can lead to significant declines in fitness and fertility, and even extinction[94]. However, there is evidence that populations can mitigate their deleterious effects and prevent a continuous decline in fitness[95]. The SPD from El Hierro suggests that low genetic diversity did not affect the fertility rate or the ability of the population to increase its demographic traits after the bottleneck episode.

European expansion and Amazigh demographic decline

The results of our study also have implications for the impact of European expansion on indigenous populations[96]. The demography of the Amazigh communities experienced a dramatic disruption in the form of a decline at approximately 1350 cal CE, which can be directly linked to European contacts. Canarian island societies were systematically dismantled by a process initiated by European slave raiders in the early fourteenth century, which reached a climax with the arrival of Iberian conquerors and settlers in the late fifteenth century[22]. Their arrival was characterized by unrestrained violence, almost complete confiscation of land, and nearly enslavement and deportation of the indigenous population[97,98]. Furthermore, these findings coincide with the introduction of lethal pathogens among Amazigh populations[35]. The entire archipelago was conquered by the Crown of Castilla in 1496, and the remaining indigenous inhabitants were forced to abandon their traditional ways of life and adopt the social norms of the conquerors[20,99]. The results presented here therefore provide compelling evidence of this demographic and cultural catastrophe.

Research limitations

Although the present results support the idea that climatic fluctuations played a role in the population dynamics of the Canary Islands during the Amazigh period, several potential limitations must be recognized. The archipelago, for example, has experienced significant volcanic activity over the past 500 years, as documented in archives[100], which at times has had a significant impact on the availability of resources[101,102]. This is exemplified by the 2021 eruption on the island of La Palma, when agricultural fields were covered with lava and ash. However, there is a lack of accurate data on volcanic activity prior to European colonization[103], so future research should explore the impact of these eruptions during the Amazigh period.

High-resolution climatological and ecological records of the Canary Islands are also still scarce and limited to a few proxies[28,29,45,46]. Furthermore, the distributions of radiocarbon dates collected from different islands are not uniform. Most come from Gran Canaria, whereas the islands of Lanzarote and Fuerteventura are significantly underrepresented (Supplementary Note 3).

Future research should therefore prioritize these less studied islands to ensure a comprehensive understanding of the region. Further integrated paleoclimate research is needed to disentangle the dynamics between island populations and climate variability. In addition, the long-term trajectories of island societies are crucial for defining human‒environment interactions under different climate regimes and at different spatial and temporal scales. Further research examining changes in archaeological records during periods of climate change is needed to determine the social and ecological thresholds and past responses of Amazigh populations. The results of this study suggest a link between NAO oscillations, temperature and island population demography. However, the lack of climate models for the Canary Islands is insufficient to test the extent of climate-demography feedback, a topic that clearly merits further detailed investigation. Despite these limitations, this study contributes to a better understanding of the relationships among population dynamics, the island environment, genetic variability and climate change in the Canary Islands.

Conclusions

The results of this study shed new light on the intricate dynamics shaping the population trajectories of the Amazigh inhabitants of the Canary Islands, highlighting the complex interplay between biogeography, climate variability, and human agency. This research suggests potential links between demographic trends and environmental factors. During the RWP, favorable climatic conditions, including the negative phase of the NAO characterized by increased winter rainfall and milder temperatures, supported agricultural productivity and livestock husbandry, facilitating Amazigh colonization and demographic expansion. However, between approximately 700 and 800 cal CE, positive NAO conditions led to reduced rainfall across western North Africa and southern Iberia, triggering a significant population decline, particularly on smaller or more arid islands. This decline was characterized by the loss of staple crops, reduced effective population sizes, and genetic bottlenecks, highlighting the vulnerability of these island populations to climatic stress.

Despite these challenges, larger and more ecologically diverse islands, such as Gran Canaria and Tenerife, experienced sustained population growth during the MCA (800–1150 cal CE). Their superior carrying capacity, agricultural diversity, and long-term food storage allow them to be resilient to environmental fluctuations. These findings highlight the central role of agricultural diversification in enhancing human resilience to environmental change, which often drives demographic expansion. The biogeographic diversity of islands such as Gran Canaria and Tenerife enabled sustained growth, whereas islands with limited agricultural heterogeneity followed different trajectories. Charcoal analyses from this period also revealed shifts in arboreal composition and intensified anthropogenic impacts, illustrating the reciprocal relationship between human activity and ecological change.

From 1150 to 1350 cal CE, there was a demographic boom in both desert-like and Mediterranean-like environments. Gran Canaria, in particular, was characterized by advanced agricultural practices, food storage infrastructure, and irrigation systems that improved food security. Cooler sea surface temperatures (1000–1500 cal CE) and a prevailing negative NAO phase (1300–1600 cal CE) increased marine and agricultural productivity, further supporting population growth. Even islands with reduced genetic diversity, such as El Hierro, showed remarkable resilience during this period, highlighting the inherent capacity of human societies to recover and thrive in changing environmental landscapes.

The arrival of Europeans in the fourteenth and fifteenth centuries CE, however, marked a turning point in the history of the Canary Islands. The introduction of slave raids, novel pathogens, and land confiscation led to severe demographic and cultural upheavals, ultimately leading to the collapse of indigenous Canarian societies. Although the Amazigh communities showed resilience in adapting to environmental challenges over the centuries, these external forces proved insurmountable and signaled the end of a remarkable chapter in the demographic history of the Canary Islands.

Methods

Sample selection

The dataset used in this study comprises 648 radiocarbon datings ranging from 2000 to 400 BP (uncalibrated) from samples collected at Amazigh archaeological sites throughout the archipelago (Supplementary Note 3 and Supplementary Data 1, Fig. S1). These radiocarbon dates were subjected to a chronometric hygiene protocol described recently[18] to ensure their reliability and integrity. The dataset thus included only Class 1 and 2 radiocarbon dates (Supplementary Data 1). Class 1 included short-lived terrestrial samples identified at the species level via accelerator mass spectrometry (AMS). The samples had to be from secure cultural layers bearing laboratory names and numbers. Class 2 comprised unidentified wood charcoals, long-life terrestrial samples, marine shells identified at the taxon level and human samples from secure contexts bearing a laboratory name and number (Supplementary Data 1).

Quantitative analyses of summed probability distributions (SPDs)

R programming language and the software package *rcarbon* served to design the Summed Probability Distribution (SPD) plots[41] (Supplementary Note 4 and Supplementary Data 2). The IntCal20 and Marine20 calibration curves were applied, depending on the nature of the sample, to calibrate the radiocarbon dates[104,105]. The radiocarbon analyses of human remains were calibrated by means of a curve comprising 87% terrestrial and 13% marine elements of the diet. The specific offset and error of the marine reservoir effect were considered following the findings of Santana et al.[18] (Fig. S2).

Several techniques were employed to minimize the biases of the Summed Probability Distribution (SPD) plots[41,60]: (1) a chronometric hygiene protocol to screen data aimed at excluding unreliable or questionable elements (Supplementary Data 1); (2) resorting to radiocarbon dates directly associated with anthropogenic activities, notably only Class 1 and 2 dates (Supplementary Note 3, Supplementary Tables S1 and S2); (3) grouping calibrated datings within 50-year bins to prevent the oversampling of archaeological contexts and facilitate their comparison with other archaeological proxies (Supplementary Note 4 and Supplementary Data 2); (4) use of 200-y smoothed and nonnormalized distributions of the summed radiocarbon datings to avoid artificial peaks in the SPDs stemming from sharp fluctuations of the calibration curve (Supplementary Note 4 and Supplementary Data 2); and (5) modeling the raw counts of archaeological sites and the radiocarbon datings by means of 200-year intervals (Supplementary Note 5, Tables S3–S7).

These strategies were implemented to increase the reliability and accuracy of both the analyses and interpretations of the SPDs related to population dynamics[41,60]. Several models were subsequently developed that focused on island features (desert-like and Mediterranean-like climates) and genetic diversity (high and low) with reference to each individual island (Lanzarote, Fuerteventura, Gran Canaria, Tenerife, La Gomera, La Palma, and El Hierro) (Supplementary Notes 1 and 2). Resorting to these factors allowed us to assess their impact on population dynamics and explore how changes in island ecosystems, including features linked to climate and the environment, may have influenced island demographics.

Statistical correlation analysis of the SPD curves and climatic proxies

To examine the relationships between the SPD curves and climatic proxies, both datasets were first interpolated onto an annual temporal scale via linear interpolation. This procedure ensured comparability, as the original datasets differed in temporal resolution and contained irregular sampling intervals. Subsequently, Pearson's correlation coefficient was calculated, along with statistical significance testing ($\alpha = 0.05$), to evaluate the strength and direction of this relationship. Given Pearson's correlation assumptions of linearity and independence among observations, the suitability of this approach was assessed considering the specific characteristics of the data[106]. Correlation analyses were conducted for the entire indigenous occupation period as well as separately for each phase of demographic change identified in the SPD curves of both Mediterranean-like and desert-like islands.

Data availability

All the study data and codes used are included in the article and/or supporting information.

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Declarations

Competing interests
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