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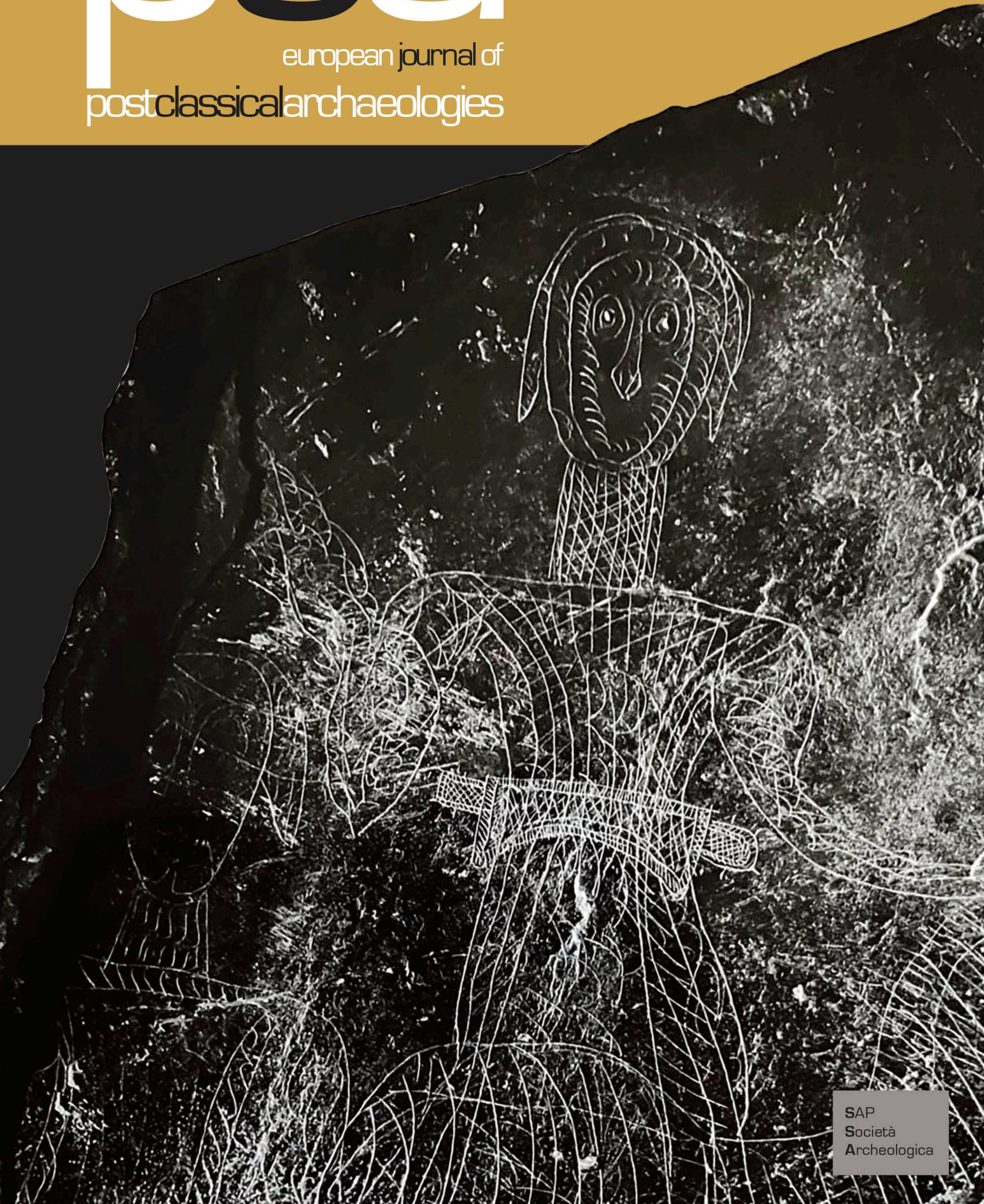

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CONTENTS PAGES

Christophe Lécuyer*

Climate change and dietary adaptation in the pre-Hispanic population of Gran Canaria, Canary Islands (Spain)

1. Introduction

The study of past human-environment interactions offers critical insights into how societies adapt to climate variability. In the North Atlantic region, the last two millennia encompass two prominent climatic phases (Le Roy Ladurie 1971): The Medieval Warm Period (MWP, ca. 1000-1300 AD) and the Little Ice Age (LIA, ca. 1300-1850 AD). The MWP was characterised by generally warmer temperatures and, in many regions, more favourable agricultural conditions (Mann *et al.* 2009). In contrast, the LIA brought cooler climates, increased storm frequency, and, in some locations, heightened aridity (Lamb 1980; Athimon, Maanan 2018). The LIA was characterised by a succession of cooling events, each distinguished by low sunspot activity, diminished solar irradiance, and reduced magnetism (Easterbrook 2016). In Europe, many societies demonstrated heightened vulnerability and diminished resilience during periods of extreme storm activity impacting the English, Dutch, Danish and German coasts (e.g. Lamb 1980; Athimon, Maanan 2018). Numerous hypotheses have been advanced to elucidate the anomalous climatic conditions of the LIA. As demonstrated in the works of several authors (DeMenocal *et al.* 2000; Maslin *et al.* 2001; Paasche, Bakke 2010; Henke *et al.* 2017; Ilyashuk *et al.* 2019; Fang *et al.* 2019), it was hypothesised that the LIA was initiated by a major shift in atmospheric circulation patterns of the Intertropical Convergence Zone (ITCZ), the West African Monsoon (WAM), the Northern Annular Mode (NAM) also called the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO) and the El Niño–Southern Oscillation (ENSO).

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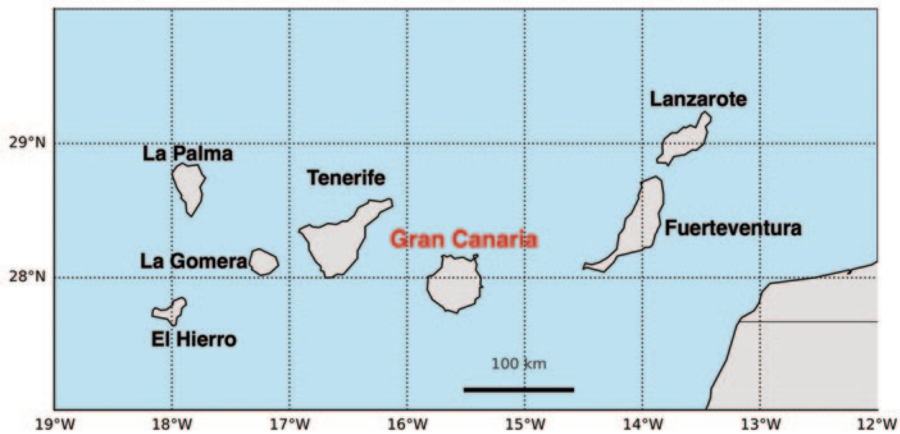

Fig. 1. Geographic map of the Canary Islands, Spain.

Gran Canaria, part of the Canary Archipelago situated about 200 km off the northwest coast of Africa (fig. 1), occupies a strategic position for understanding the effects of the MWP–LIA transition at low latitudes in the eastern North Atlantic. Its climate is shaped by the interplay of the Canary Current, the North Atlantic Oscillation (NAO), and the seasonal migration of the Intertropical Convergence Zone (ITCZ). The island steep topography creates strong climatic gradients over short distances, with higher-altitude interiors typically cooler and wetter than low-lying coastal areas. These gradients would have influenced resource availability, agricultural potential, and access to marine versus terrestrial foods for pre-Hispanic communities.

Previous research by Lécuyer *et al.* (2021) provided a robust chronological and geochemical framework for this period. Through radiocarbon dating (fig. 2) and stable isotope analyses of carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$), oxygen ($\delta^{18}O$), and sulfur ($\delta^{34}S$) in the collagen of human bone remains from pre-Hispanic individuals, they reconstructed aspects of palaeodiet and palaeoclimate on Gran Canaria. Their work revealed a clear isotopic signal for climatic cooling between the MWP and the LIA, supported by oxygen isotope evidence, which aligns with broader regional palaeoclimate reconstructions (DeMenocal *et al.* 2000; Esper *et al.* 2007).

Archaeological evidence shows that pre-Hispanic settlement patterns on Gran Canaria (fig. 3) were diverse and closely tied to environmental conditions (Morales *et al.* 2014; Morales 2019; Velasco Vázquez *et al.* 2019). Coastal areas hosted communities with easier access to marine resources, fishing grounds, and potential trade routes, while interior valleys and upland zones supported agricultural terraces and pastoral activities. Seasonal mobility, resource special-

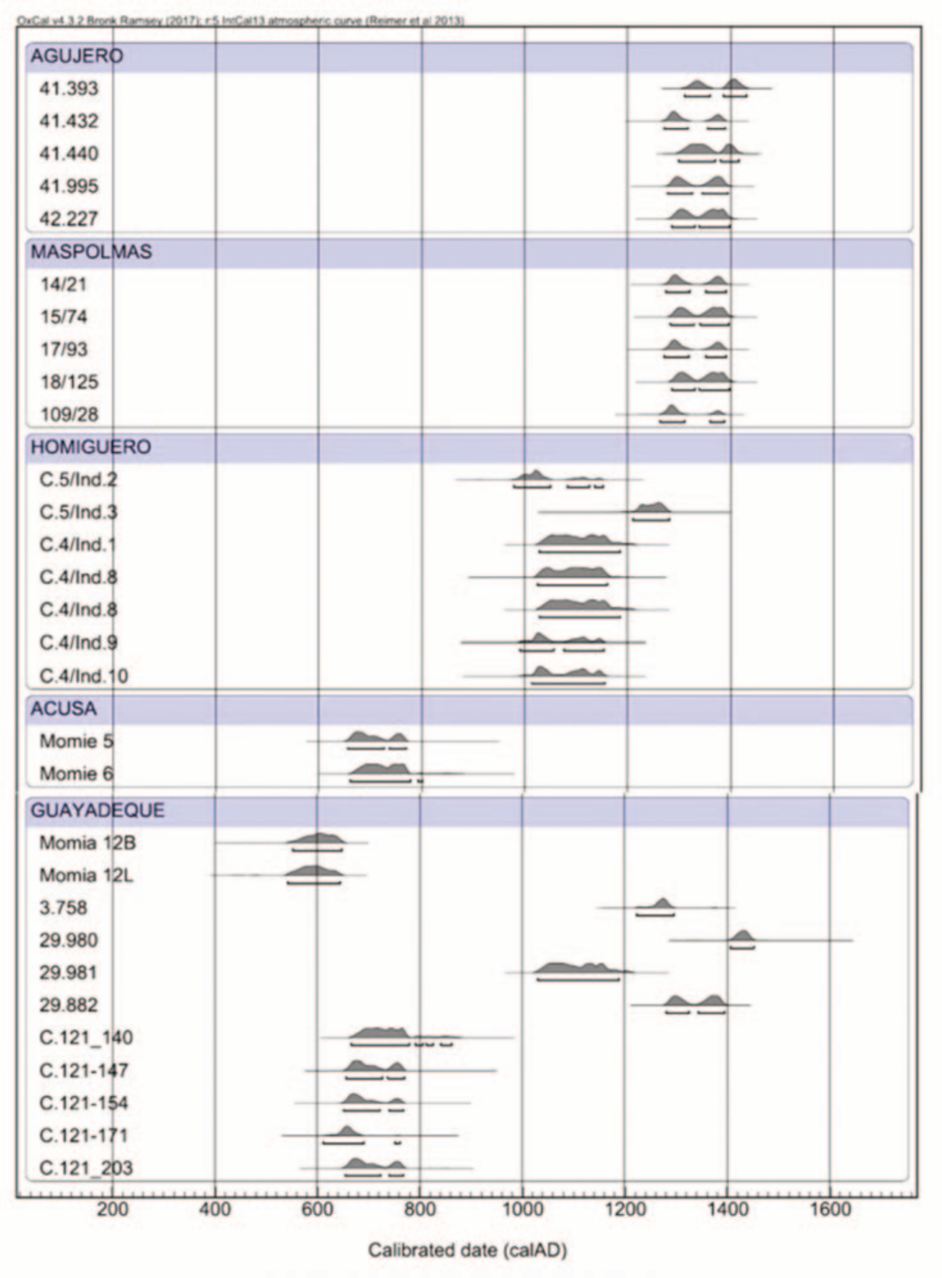

Fig. 2. Compilation of calibrated ^{14}C dates of human and animal collagen from the archeological sites located in Figure 3. Source of data is Lécuyer *et al.* (2021). Calendar ages were determined using OxCal v4.3.2 software (Bronk Ramsey, Lee 2013). The calibration results are considered within a 2-sigma interval, i.e. a 95.4% confidence level, and are expressed in calendar years BC or AD (before or after Christ).

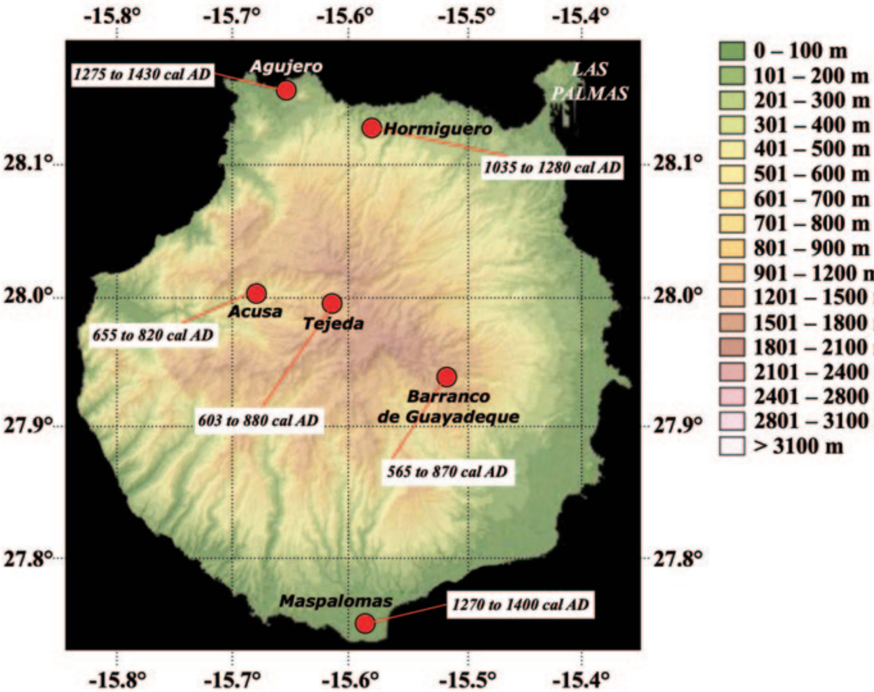

Figure 3: Map of Gran Canaria showing archaeological sites included in the study. Sites dated to the MWP and LIA are indicated, illustrating the later shift toward coastal occupation. Modified after Lécuyer *et al.* (2021).

isation, and the exploitation of distinct ecological zones likely created a mosaic of subsistence strategies across the island. Any climatic shift affecting rainfall regimes, crop yields, or marine productivity would thus have had uneven impacts depending on settlement location, potentially driving shifts in dietary composition between communities and over time.

While previous work established that environmental conditions shifted significantly across this climatic transition, it left open a key question: to what extent did these changes in climate translate into changes in human subsistence strategies? Specifically, can we quantify shifts in the relative contribution of marine versus terrestrial resources, and plant versus animal foods, to the diet of Gran Canaria's pre-Hispanic population between the MWP and LIA?

The present study addresses this question by applying quantitative inverse modelling approaches – namely, least-squares optimisation and Bayesian mixing models – to the isotopic dataset of Lécuyer *et al.* (2021). By integrating isotopic baselines for potential food sources with appropriate trophic enrichment factors, we estimate dietary proportions for the MWP and LIA, and assess the magnitude and direction of dietary change in relation to climatic cooling. This modelling framework represents a methodological advance over earlier qualitative and semi-quantitative interpretations of isotopic offsets, providing statistically constrained dietary reconstructions that can be directly compared between climatic periods. In doing so, the study offers a novel example of how inverse modelling can bridge archaeological, palaeoclimatic, and geochemical evidence to evaluate the adaptive responses of past insular societies to environmental variability.

2. Archaeological and settlement background

The Canary Islands were settled in the early centuries of the 1st millennium AD by peoples of North African Amazigh origin, as confirmed by genetic, linguistic, and material culture evidence (Fregel *et al.* 2019; Velasco Vázquez 2014; Rodríguez-Varela *et al.* 2017). Once established, Gran Canaria's population developed a distinctive socio-economic system adapted to the island rugged terrain, with central mountains rising nearly 2,300 m above sea level (fig. 3) and a mosaic of ecological zones (Morales *et al.* 2014; Morales 2019).

From the earliest stages, subsistence was anchored in an agro-pastoral economy. Domesticated crops – primarily barley (*Hordeum vulgare*), wheat (*Triticum aestivum/durum*), figs (*Ficus carica*), and pulses – formed the agricultural base, complemented by livestock (goats, sheep, pigs) and the gathering of wild resources such as Canarian palm dates (*Phoenix canariensis*) (Morales 2019; Morales *et al.* 2014; Hagenblad *et al.* 2017). Archaeological evidence shows the construction of large communal granaries, often carved into volcanic tuff, indicating the importance of long-term grain storage to buffer against seasonal shortages (Alberto *et al.* 2017).

Fishing and shellfish gathering were also practised, particularly in coastal communities. Species such as parrotfish (*Sparisoma cretense*), anchovy (*Engraulis encrasicolus*), and limpets (*Patella* spp.) appear in coastal middens, though earlier inland populations show a stronger emphasis on terrestrial resources (Rodríguez Santana 1996).

Inland and upland zones dominated early settlement, particularly fertile valleys and ravine mouths that offered arable land and access to seasonal water sources. By the 11th century, settlement patterns began to diversify. A gradual increase in coastal occupation is visible in the archaeological record, culminating in more extensive coastal village sites during the 13th-14th centuries. This shift coincides temporally with the onset of the LIA and may reflect both demographic pressures and environmental change (Delgado-Darias *et al.* 2023).

Burial practices shifted over time from collective cave interments in proximity to habitation sites to larger necropolises featuring stone cists and pit graves, particularly along the coast in the later period (Santana Cabrera *et al.* 2012; Alberto

Fig. 4. Photograph of a human mummy preserved at the El Museo Canario, Las Palmas, Gran Canaria, Canary Islands, Spain. Crédit: C. Lécuyer.

et *al.* 2014; Velasco-Vázquez *et al.* 2019; Delgado-Darias 2020). These changes are interpreted as reflecting both internal social developments and possible external influences from North Africa (Alberto *et al.* 2019; Fregel *et al.* 2019), but they also provide chronological anchors for isotopic sampling of human remains from inland and coastal contexts (Arnay-de-la-Rosa et al. 2010; Lécuyer *et al.* 2021; Sánchez-Cañadillas *et al.* 2023).

It is worthy to note that Human bodies have been naturally mummified in a dry environment and wrapped with rush fibers and animal leather, thus allowing a very good preservation (Henríquez-Valido *et al.* 2019; Vidal-Matutano *et al.* 2020) of both hard and soft tissues (fig. 4). Such preservation conditions are ideal for isotopic analysis of these tissues, as is the case with ancient Egyptian mummies (Touzeau *et al.* 2013).

Stable oxygen isotope analysis of human skeletal apatite phosphate provides a proxy for the isotopic composition of drinking water, which in turn reflects local meteoric precipitation (Longinelli 1984; Luz *et al.* 1984). In this study, values were corrected for altitude effects (Lécuyer *et al.* 2021) to enable comparison between individuals from different elevations and to approximate sea-level conditions.

The results show a decrease in $\delta^{18}O$ values from the MWP to the LIA, corresponding to a cooling of approximately 4-5°C (Lécuyer *et al.* 2021). This finding is supported by independent lines of evidence. Sediment core records from offshore Mauritania reveal similar declines in sea-surface temperature (SST) of 3-4°C around 1300 AD (deMenocal *et al.* 2000 while marine proxy studies from the western Canary Islands indicate that SSTs during the Medieval Warm Period

(MWP) were comparable to modern conditions (around 21-22°C). These were then followed by notable cooling at the onset of the Little Ice Age (Parker *et al.* 2020; Lécuyer *et al.* 2021).

This shift occurred at a time that coincided with a large-scale reorganization of the climate in the North Atlantic, which was likely driven by reduced solar irradiance and changes in oceanic circulation. These changes included the weakening of the subtropical gyre and the southward displacement of the Intertropical Convergence Zone (ITCZ). (Lund *et al.* 2006; Sachs *et al.* 2009; Paasche, Bakke 2010). While most well-resolved LIA records derive from higher latitudes (e.g. Lamb 1980; Athimon, Maanan 2018), the Gran Canaria isotope record shows that the cooling event extended into low-latitude subtropical islands, with measurable implications for terrestrial water isotopes and, potentially, subsistence systems (Lécuyer *et al.* 2021).

3. Methods: Human diet reconstruction based on inverse modelling

3.1. A Python code using both Least Squares method and probabilistic Bayesian mixing models

The Python code has been developed by the author with the help of the deep learning machine ChatGPT 4.0. This is a custom code that offers several advantages over public software such as FRUITS, particularly in terms of flexibility and transparency. A major strength lies in the user ability to directly customize every aspect of the analysis, from defining trophic enrichment factors and baseline uncertainties to setting the number of draws and tune iterations in the Bayesian Markov Chain Monte Carlo (MCMC) sampling. This allows researchers to fine-tune computational precision versus runtime and explore sensitivity under different assumptions, something that black-box software often restricts. Moreover, because the code is open and written in standard libraries like “NumPy”, “SciPy”, and “PyMC”, users can easily adapt functions, integrate new isotopes, or export results in custom formats (CSV, SVG). On the other hand, compared to polished platforms like FRUITS, this script requires programming skills, and less experienced users may find debugging or modifying models challenging. The graphical outputs, while functional, are less interactive than those in specialized software, and model validation is entirely the user responsibility. In short, this code trades ease of use and built-in validation for complete control, reproducibility, and adaptability, making it especially valuable for advanced users who need to experiment with model structures or tailor MCMC parameters such as “draws” (the saved estimates of dietary proportions, which together provide the distribution and credible intervals) and “tune” (the warm-up stage stabilizig the algorithm before collecting results).

This Python script estimates dietary proportions from isotopic measurements of human collagen that have been published in Lécuyer *et al.* (2021). It focuses on three food groups: Plants, Meat (terrestrial animal protein) and Fish (aquatic protein). Using isotopic data of Carbon (C), Nitrogen (N), and Sulfur (S), the script provides two complementary methods to estimate the diet composition:

1. Least Squares Model with trophic enrichment factors and uncertainty estimation via Monte Carlo simulation.
2. Bayesian Mixing Model using probabilistic inference to estimate proportions with credible intervals.

Isotopic analyses of collagen provide insight into an individual diet by measuring the stable isotope ratios ($\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$). These reflect the isotopic signatures of consumed foods plus systematic isotopic enrichment (Trophic Enrichment Factors, TEFs) occurring when moving up trophic levels (e.g., plants to herbivores to humans and fish to humans). In the python code available as Supplementary file#1 and its notice available as Supplementary file#2, some parameters have been fixed as follows:

- Trophic enrichment for Carbon is assumed to be +2‰ per trophic level.
- Trophic enrichment for Nitrogen is assumed to be +3‰ per trophic level.
- Sulfur isotopes are assumed not to have trophic enrichment.

Users can customize these values and the baseline isotopic values for each food source.

Data inputs are:

- Human isotopic values: A database containing observed isotopic ratios for C, N, and S in human collagen.
- Baseline sources: Isotopic values for plants, meat, and fish, representing the environmental baseline.
- Trophic jumps: Number of trophic levels jumped from each source to human.
- Trophic Enrichment Factors (TEF): Per trophic level enrichment for C and N isotopes.
- Analytical errors: Measurement uncertainties for C, N, and S isotopic ratios used in uncertainty estimation.

3.2. The Least Squares Model

The least squares model (e.g. Bryan *et al.* 1969; Olivieri 2018) estimates dietary proportions by solving the linear system:

$$Ax = b$$

where:

$$\mathbf{A} = \begin{bmatrix} \delta^{13}C_{\text{plants}} + \text{TEF}_C \times J_{\text{plants}} & \delta^{13}C_{\text{meat}} + \text{TEF}_C \times J_{\text{meat}} & \delta^{13}C_{\text{fish}} + \text{TEF}_C \times J_{\text{fish}} \\ \delta^{15}N_{\text{plants}} + \text{TEF}_N \times J_{\text{plants}} & \delta^{15}N_{\text{meat}} + \text{TEF}_N \times J_{\text{meat}} & \delta^{15}N_{\text{fish}} + \text{TEF}_N \times J_{\text{fish}} \\ \delta^{34}S_{\text{plants}} & \delta^{34}S_{\text{meat}} & \delta^{34}S_{\text{fish}} \\ 1 & 1 & 1 \end{bmatrix}$$

$$\mathbf{b} = \begin{bmatrix} \delta^{13}C_{\text{human}} \\ \delta^{15}N_{\text{human}} \\ \delta^{34}S_{\text{human}} \\ 1 \end{bmatrix}$$

and x is the vector of dietary proportions (plants, meat, fish). A constrained least squares approach enforces proportions to be between 0 and 1 and sum to 1. Analytical errors are modeled as Gaussian noise added to the human isotopic values. The least squares model is run repeatedly (default 5,000 simulations), producing distributions of dietary proportions. The mean and standard deviation of these distributions estimate the dietary proportions and their uncertainties. A flow chart is provided to illustrate the way the first part of the Python code logically works (fig. 5).

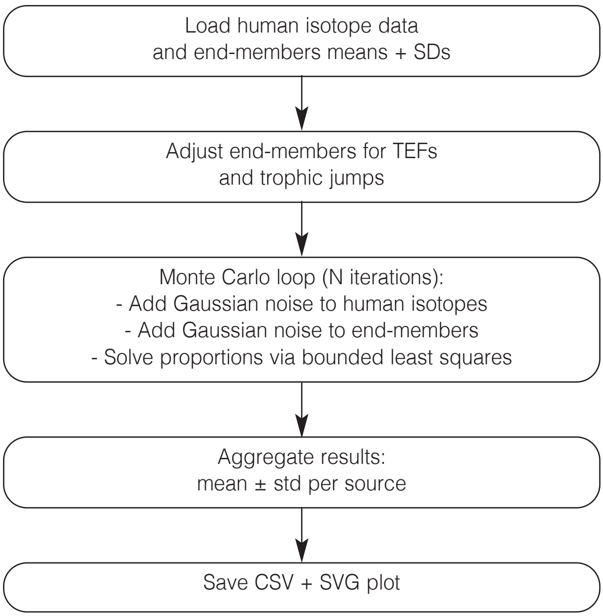

Fig. 5. Workflow diagram for the least-squares Monte Carlo framework. The model adjusts isotope baselines for trophic enrichment factors (TEFs) and trophic jumps, then runs Monte Carlo iterations (n = 5000) with Gaussian noise added to both human and baseline isotope values. Proportions are solved using bounded least-squares, and the results are aggregated as mean ± standard deviation for each dietary source.

3.3. Bayesian Mixing Model

In this study, a Bayesian dietary mixing model (Berger 1985; Bernardo, Smith 2009; Taboga 2021) was used to estimate the proportional contributions of plants, terrestrial meat, and marine fish to the diet by integrating prior information with observed isotope data. Dietary proportions were assigned a Dirichlet prior ($\alpha = 1$), while baseline isotope values were modelled as normal distributions centered on measured means, with standard deviations reflecting baseline uncertainty. The likelihood function links these dietary proportions to the human isotope measurements, explicitly incorporating combined measurement and analytical errors. Posterior distributions were obtained through Markov Chain Monte Carlo (MCMC) sampling, in which each proposed set of parameters depends only on the previous state (Markov property). Iterative sampling allows the chains to converge on a stationary distribution whose relative frequencies approximate the true posterior probability distribution of dietary proportions. After discarding initial burn-in iterations, the remaining samples yield robust estimates of the mean, variance, and 95% Highest Density Intervals (HDIs) for each dietary source. This probabilistic framework accounts for uncertainty in both baseline values and measurements, producing reconstructions that represent the full range of plausible dietary compositions supported by the data. A flow chart is provided to illustrate the way the second part of the Python code logically works (fig. 6).

4. Results: Dietary reconstruction from $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values

Lécuyer *et al.* (2021) estimated a ratio of 95% seed/cattle to 5% seafood during the MWP, and 89% seed/cattle to 11% seafood during the LIA. Consequently, the LIA diet appears to have contained about 6% more seafood than the MWP diet, which is consistent with the coastal locations of Maspalomas and Agujero.

The mean stable isotope compositions (C, N and S) of human bone collagen from the MWP and LIA periods (fig. 7), the compositions of food baselines (plants, cattle and fish), the analytical uncertainties, standard deviations around the mean values for human measurements and baseline measurements or estimates (fish), trophic enrichment factors (TEFs) and trophic jumps (TJ) for plants, cattle and fish are reported in table 1.

4.1. Least-squares Monte Carlo estimates of dietary contributions

Applying the adjusted baseline values (with TEFs and trophic jumps) to the human isotope dataset, the Monte Carlo–enhanced least-squares model yielded a diet composition heavily weighted towards low trophic level resources.

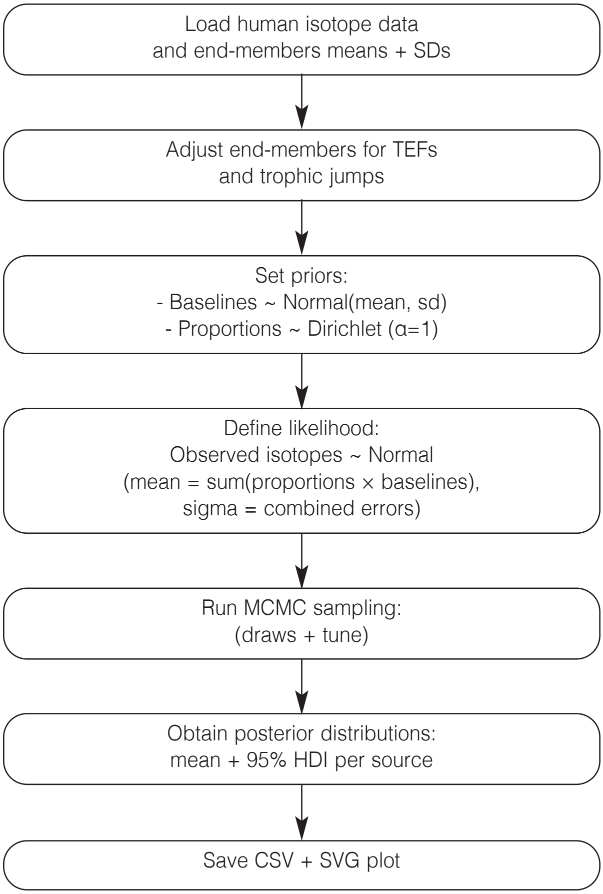

Fig. 6. Workflow diagram for the Bayesian mixing model framework. Baseline isotope values are treated as normal distributions, and dietary proportions follow a Dirichlet prior. The likelihood links observed human isotope values to weighted baseline values. Markov Chain Monte Carlo (MCMC) sampling produces posterior distributions for each dietary source, summarised by mean and 95% highest density intervals (HDIs).

During the MWP, mean estimated dietary proportions were:

- Plants: 0.73±0.13
- Terrestrial meat: 0.13±0.18
- Marine fish: 0.14±0.07

While during the LIA, we obtain:

- Plants: 0.66±0.14
- Terrestrial meat: 0.13±0.19
- Marine fish: 0.21±0.08

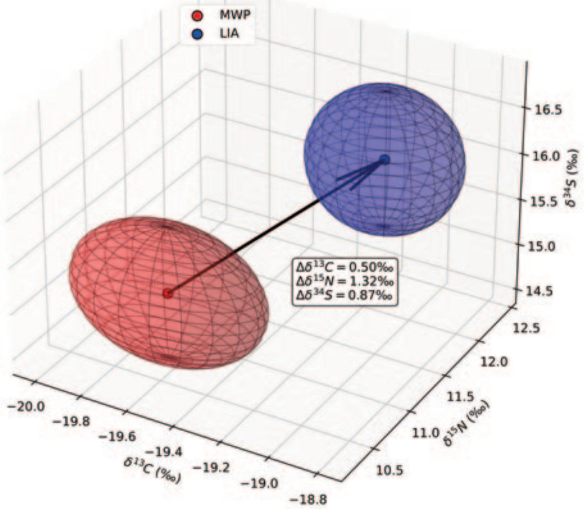

Fig. 7. 3D-plot comparing the mean δ13C, δ15N and δ34S values of human bone collagen for the Medieval Warm Period (MWP) and the Little Ice Age (LIA). The ellipsoid surfaces (MWP: red, LIA: blue) are defined by their three main axes that correspond to the uncertainties associated with the measured δ13C, δ15N and δ34S values. The black arrow illustrates the increase in these three isotopic proxies between these two periods, which are consistent with higher marine food consumption. Data sources from Lécuyer *et al.* (2021).

Period/Food	**δ13C**	**S.D.**	**δ15N**	**S.D.**	**δ34S**	**S.D.**	**TEF**
	(‰ PDB)	(‰ AIR)	(‰ CDT)				
Human collagen:							
MWP	-19.60	0.41	10.61	0.38	15.22	0.71	N/A
LIA	-19.10	0.31	11.93	0.48	16.09	0.73	N/A
Baselines:							
Plants	-23.07	1.64	4.63	0.61	14.00	0.50	1
Cattle	21.11	0.65	7.43	0.71	14.00	0.50	2
Fish	-12.00	0.50	14.00	0.50	21.00	0.50	3
TJ	1.00	N/A	3.20	N/A	0.00	N/A	N/A
Analytical. Uncertainties (1σ)	0.08	N/A	0.14	N/A	0.18	N/A	N/A

Table 1. Observed isotopic ratios for C, N, and S in human collagen along with baseline sources: Isotopic values for plants, meat, and fish, representing the environmental baseline. TJ = Trophic jumps: Number of trophic levels jumped from each source to human. TEF = Trophic Enrichment Factors: Per trophic level enrichment for C and N isotopes. Analytical errors: Measurement uncertainties for C, N, and S used in uncertainty estimation. S.D. = standard deviation. N/A/ = not applicable. Data sources from Lécuyer *et al.* (2021).

4.2. Bayesian mixing model estimates of dietary contributions

The Bayesian mixing model, incorporating baseline uncertainties and combined measurement–analytical errors, produced a markedly different dietary composition compared to the least-squares approach.

During the MWP, mean estimated dietary proportions were:

- Plants: 0.66 (95% CI: 0.45 – 0.87)
- Terrestrial meat: 0.24 (95% CI: 0.001 – 0.509)
- Marine fish: 0.10 (95% CI: 0.00 – 0.19)

While during the LIA, we obtain:

- Plants: 0.53 (95% CI: 0.215 – 0.76)
- Terrestrial meat: 0.31 (95% CI: 0.004 – 0.723)
- Marine fish: 0.16 (95% CI: 0.02 – 0.27)

The least-squares Monte Carlo and Bayesian mixing models produce notably different reconstructions for both climatic periods. For the MWP, least-squares suggests a diet dominated by plants with roughly equal contributions from terrestrial meat and marine fish, whereas Bayesian analysis reconstructs a similar plant share but assigns proportionally more to meat and less to fish. For the LIA, least-squares estimates a reduced plant share and a marked increase in fish consumption relative to meat, while the Bayesian model also shows a plant decline but indicates a balanced increase in both meat and fish. Compared to Lécuyer *et al.* (2021), both models agree on a relative rise in marine resources during the LIA, yet differ in the extent to which terrestrial protein sources contributed, underscoring how methodological assumptions influence dietary reconstructions.

The divergence between methods underscores the importance of employing multiple modelling frameworks to bracket plausible dietary reconstructions. It also highlights that, for Gran Canaria pre-Hispanic populations, both terrestrial-marine protein exploitation and plant agriculture were potentially significant, with their relative prominence depending on the analytical approach adopted.

5. Discussion

5.1. Settlement shifts and resource access during the LIA

The Bayesian inference model utilised in this study, which incorporates three isotopic proxies ($\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$), has enabled the estimation of the proportion of marine food in the diet of the pre-Hispanic populations of Gran Canaria at approximately 16%. This estimate is higher than that proposed by Lécuyer *et al.* (2021) but is more closely aligned with the estimates calculated by Sánchez-Cañadillas *et al.* (2023) using the “FRUITS” software applied to $\delta^{13}C$

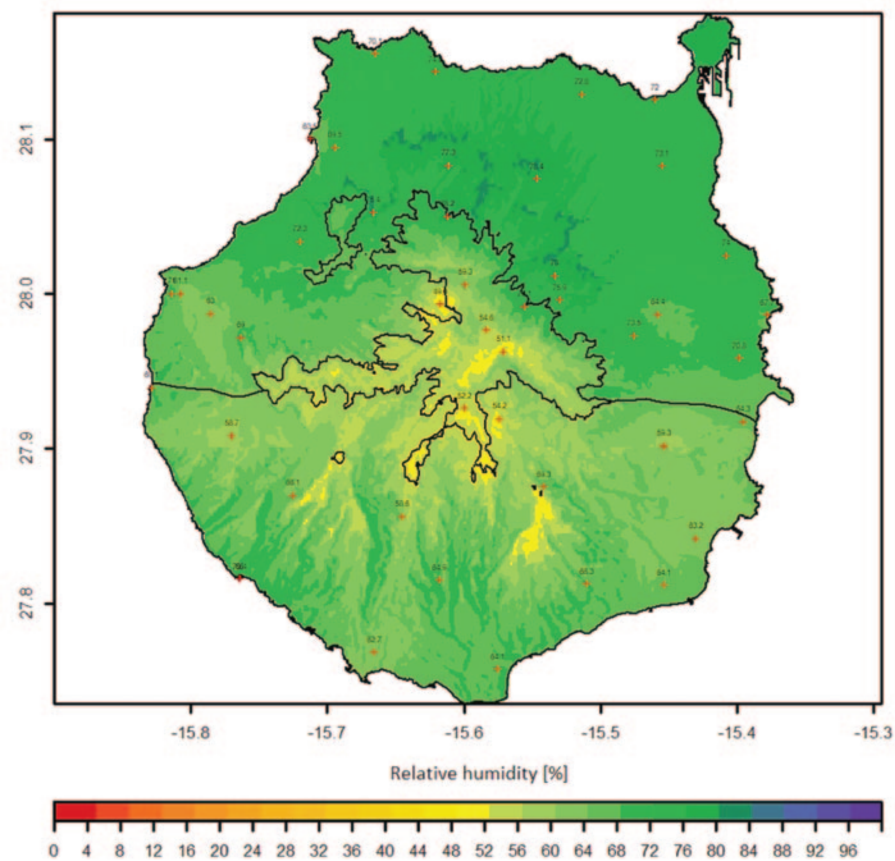

Fig. 8. Mean annual geographic distribution of the relative air humidity (RH) in Gran Canaria, Canary Islands, Spain. Data source: http://mapadeconfortclimaticodegrancanaria.blogspot.com/2012/07/mapa-mensual-de-humedad-relativa.html.

and $\delta^{15}N$ values of tooth dentine collagen increments. The results of this study are also consistent with the conclusions drawn by Arnay-de-la-Rosa *et al.* (2010), who recommend a high intake of animal protein from land and sea sources during the LIA. All these isotope evidence align closely with archaeological patterns of settlement change (fig. 3). During the earlier phases of occupation, particularly from the 7th to the 11th century, major population centres were located inland (fig. 3), often in fertile valleys and upland areas with a reliable supply of seasonal water (fig. 8). These areas supported intensive cereal cultivation, complemented by livestock herding and the gathering of wild plant foods (Morales *et al.* 2014; Henríquez-Valido *et al.* 2019). Coastal occupation existed but was limited, often

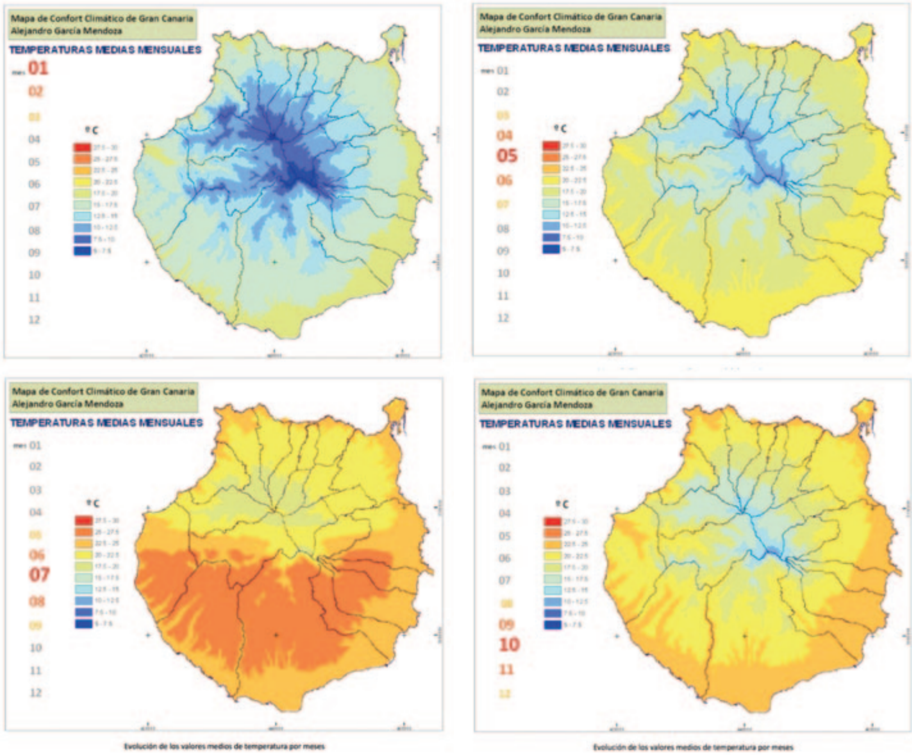

Fig. 9. Geographic distribution of the monthly air temperature (T°C) for January (01), May (05), July (07) and October (10) in Gran Canaria, Canary Islands, Spain. Data sources: De Luxán Garcia de Diego, Reymundo Izard (2011) and Söllheim *et al.* (2024). https://thefutureofeuropes.fandom.com/wiki/The_Dynamic_Island_(Map_Game)

associated with seasonal fishing or shellfish gathering rather than permanent residence (Morales *et al.* 2009; Parker *et al.* 2020; Delgado-Darias *et al.* 2023; Aberto-Barroso *et al.* 2024).

By the 13th and 14th centuries, the archaeological record shows a marked increase in permanent coastal settlements (fig. 3). Large, stone-built villages such as those at Agujero and Maspalomas, with associated pit- and cist-style cemeteries, appear during this period (Eddy 1998). These sites coincide chronologically with the LIA onset and the cooler conditions inferred from $\delta^{18}O$ data (Lécuyer *et al.* 2021). Coastal zones likely offered several advantages under these new climatic constraints such as an access to marine resources that provided a reliable supplementary protein source and milder microclimates in winter (fig. 9).

5.2. Resilience and adaptation

The combined archaeological and isotopic evidence suggests that the pre-Hispanic inhabitants of Gran Canaria were highly resilient in the face of climate change (Lécuyer *et al.* 2021). Rather than abandoning established agricultural practices, they supplemented terrestrial production with greater exploitation of marine resources. It appears that this strategy was facilitated by their skill capacity, as evidenced by the presence of fishing gear, shellfish collection, and fish remains in coastal middens (Parker *et al.* 2020), a cultural flexibility marked by a willingness to incorporate new or previously secondary food sources into the diet without undermining the central role of farming, and a storage infrastructure with a continuous use of inland and coastal granaries to buffer food supply (Morales *et al.* 2014, 2018).

From a resilience theory perspective, this pattern illustrates an adaptive response that maintains the core identity of the socio-economic system (agriculture-based) while expanding its functional diversity (Folke *et al.* 2010). This contrasts with cases elsewhere, where climatic stress has led to rapid social collapse or significant economic change. (Diamond 2005; Dugmore *et al.* 2012).

5.3. Comparative perspectives

The Gran Canaria case fits within a broader spectrum of human responses to the MWP–LIA transition. In higher-latitude regions such as Greenland and parts of northern Europe, LIA onset contributed to the decline or abandonment of settlements (e.g., the Norse in Greenland) (Arneborg *et al.* 2002; Dugmore *et al.* 2007; D'Andrea *et al.* 2011). By contrast, societies in lower-latitude, resource-diverse settings often demonstrated greater adaptive capacity, adjusting their subsistence strategies without experiencing total systemic collapse. (Mann *et al.* 2009). Similar adaptive strategies have been documented in Southern California, where increased use of marine foods by coastal groups has been observed during cooler periods (Walker, DeNiro 1986). In British Columbia, shifts in the consumption of salmon and marine mammals have been linked to environmental variability (Schwarcz *et al.* 2014). On the West African coast, deMenocal *et al.* (2000) and Weldeab *et al.* (2007) have documented adjustments in the emphasis placed on fishing and agriculture tied to shifts in the Intertropical Convergence Zone (ITCZ).

The study of pre-Hispanic populations in Gran Canaria demonstrates that populations in subtropical islands could mitigate the impact of climate change by leveraging both terrestrial and marine resources, supported by flexible settlement patterns. Modest but significant isotopic shifts show that, even when climate change does not produce dramatic archaeological 'ruptures', it can still drive subtle, measurable changes in foodways.

6. Conclusion

Between the early 7th and mid-14th centuries AD, the pre-Hispanic population of Gran Canaria experienced a significant climatic transition from the relatively warm Medieval Warm Period to the cooler and more variable conditions of the Little Ice Age. Stable oxygen isotope evidence from human remains records a decrease in $\delta^{18}O$ values equivalent to a 4-5°C drop in mean annual air temperature at the onset of the LIA. This change is consistent with broader North Atlantic proxy records and reflects large-scale atmospheric and oceanic reorganisation.

Despite this environmental pressure, archaeological and isotopic evidence together indicate that the island inhabitants maintained a predominantly terrestrial, centered on crops and livestock. The principal adaptive change was a measurable, modest increase in marine food consumption, from about 10% to 16% inferred from a Bayesian inference model. This result illustrates a shift in human settlement toward the coast during the transition between the MWP and LIA climate periods. This adaptation appears to have been gradual and strategic, leveraging coastal microclimates and rich marine resources without abandoning the inland agricultural heartland.

The Gran Canaria case illustrates that the impacts of climate change are not always expressed as abrupt societal collapse. Instead, they can manifest as progressive adjustments in settlement patterns and subsistence strategies, leaving distinct signatures in the archaeological and isotopic records. The population's resilience lay in its ability to integrate marine resources into an enduring agricultural framework, thereby ensuring continuity in food production and cultural identity despite the climatic cooling of the Little Ice Age (LIA).

Abstract
This study quantifies dietary shifts in Gran Canaria's pre-Hispanic population across the Medieval Warm Period–Little Ice Age transition using stable isotope analysis ($\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$) and inverse modelling. Least-squares optimisation and Bayesian mixing models integrate isotopic baselines, trophic enrichment factors, and uncertainties to reconstruct dietary proportions. Results indicate a predominantly terrestrial, agriculture-based diet with a modest but significant increase in marine resource consumption (from ≈ 10% to ≈ 16%) during the cooler LIA. These findings highlight gradual, strategic coastal adaptation without abandoning inland agriculture, demonstrating the resilience of low latitude insular societies to climatic cooling.
Keywords: pre-Hispanic population, Gran Canaria, climate change, diet, stable isotopes, medieval warm period, little ice age.

Questo studio quantifica i cambiamenti alimentari nella popolazione preispanica di Gran Canaria durante la transizione dal periodo caldo medievale alla piccola era glaciale utilizzando l'analisi degli isotopi stabili ($\delta^{13}C$, $\delta^{15}N$ e $\delta^{34}S$) e la modellizzazione inversa. L'ottimizzazione dei minimi quadrati e i modelli di miscelazione bayesiani integrano le linee di base isotopiche, i fattori di arricchimento trofico e le incertezze per ricostruire le proporzioni alimentari. I risultati indicano una dieta prevalentemente terrestre, basata sull'agricoltura, con un modesto ma significativo aumento del consumo di risorse marine (dal ≈ 10% al ≈ 16%) durante la più piccola era glaciale. Questi risultati evidenziano un adattamento costiero graduale e strategico senza abbandonare l'agricoltura nell'entroterra, dimostrando la resilienza al raffreddamento climatico delle società insulari a bassa latitudine.
***Parole chiave**: popolazione pre-ispanica, Gran Canaria, cambiamento climatico, dieta, isotopi stabili, periodo caldo medievale, piccola era glaciale.*

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