



Southern Arabia Population Patterns and Intensity of Cultural Exchanges Across the Holocene Humid Period

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RESEARCH PAPER

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ABSTRACT

The Early and Middle Holocene (10,000–3,000 BCE) in Southern Arabia witnessed significant climate change and variation in material culture across space and time. This study investigates the potential impact of 1) shifts in population density and 2) climatic fluctuations on the primary drivers of social development and technological innovation in this key timeframe. Our primary goal is to assess whether and to what extent climate change impacted human societies and their technological knowledge, particularly lithic technology. This research is based on a comprehensive collection of radiocarbon dates from surveyed and excavated sites ($n = 346$), the distribution of projectile points ($n = 662$) and their technological traits, and published palaeoclimatic records from cave speleothems ($n = 2$). All proxies encompass two regional case studies, i.e. Sultanate of Oman and United Arab Emirates. Long-term trends in lithic technological traits are explored using aoristic analysis to facilitate measuring their relationship with demographic (e.g., summed probability distribution of radiocarbon dates) and palaeoclimatic proxies. Our results suggest that wetter climates during the Early Holocene facilitated population growth, while increased aridity during the Middle Holocene led to population decline and potential patterns of isolation and subsequent cultural heterogeneity. Nevertheless, technological innovations and social adaptations may have played a critical role in mitigating the impacts of environmental changes. This study enhances our understanding of the complex interactions between human technological diversity, population density, and environmental fluctuations in a key period for the formation of local sociocultural trends in the eastern half of Southern Arabia.

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KEYWORDS:

Climate dynamics;
Palaeodemography; Holocene;
Southern Arabia; Neolithic;
Radiocarbon summed
probability distribution

TO CITE THIS ARTICLE:

Maiorano, MP and Bortolini, E. 2026. Southern Arabia Population Patterns and Intensity of Cultural Exchanges Across the Holocene Humid Period. *Open Quaternary*, 12: 1, pp. 1–22. DOI: <https://doi.org/10.5334/oq.151>

1. INTRODUCTION

In the recent decades, population growth studies have become pivotal to archaeological research due to their implications for subsistence strategies, ecology and adaptive mechanisms, migration, and its relationship with exogenous factors such as climate variations (Binford 1968; Shennan 2000; Roberts et al. 2019; Palmisano et al. 2021a, b). In archaeological and anthropological discussions, population dynamics are often viewed as drivers of cultural change, subsistence strategies, social complexity, socioeconomic outputs, and intra-group conflicts (Palmisano et al. 2017, 2019; Kohler et al. 2009). Early and Middle Holocene Southern Arabia (from 11.7 to 4.2 ka B.P., Walker et al. 2012) provide an excellent context for exploring this relationship. Here, 'Southern Arabia' refers specifically to Oman and the United Arab Emirates (UAE) and does not include Yemen or the southwestern portion of the Arabian Peninsula. Although we recognize the archaeological importance of these regions, it was not possible to include them here due to the present inaccessibility of lithic collections. The eastern half of Southern Arabia was characterised by diverse cultural and environmental landscapes, and experienced significant dry and wet episodes during the Late Pleistocene and Holocene, which potentially impacted the intensity and distribution of human occupation (Cremaschi et al. 2015; Preston et al. 2012, 2015; Berger et al. 2013) as well as various adaptive strategies in both coastal and inland regions (Magee 2014; Maiorano et al. 2020a, b).

Recent interest in human-environment interactions has led to numerous studies examining how human populations impacted the landscape and how population fluctuations were influenced by climatic shifts (Roberts et al. 2018; Jones et al. 2019). For instance, Palmisano et al. (2021b) investigated the relationship between population trends and climate change in Southwest Asia from 14,000 to 2500 years ago. They found that, during the Late Pleistocene and Early Holocene, population growth corresponded with wetter climates. In the Middle Holocene, regional demographic patterns became more distinct, and by the Late Holocene interregional differences emerged. This suggests that the examined societies developed greater resilience to gradual climate shifts through advancements in infrastructure, organization, and technology (Roberts et al. 2018; Palmisano et al. 2021b).

1.1 DEMOGRAPHIC TRENDS IN ARCHAEOLOGICAL RESEARCH

Over the past 40 years, research on demographic trends at local, continental, and global scales has become a fundamental aspect of archaeological investigation. This research aims to identify some of the processes underlying sociocultural change and the interactions between humans and the environment at both contextual and cross-cultural levels (Feinman

2011; Goldewijk et al. 2010; Reba et al. 2016; Shennan 2000, 2001; Stephens et al. 2019). Recent studies have emphasized methodological advancements in reconstructing demographic fluctuations in prehistoric continental Europe, the Mediterranean, and northern Africa. These studies focus in particular on how well palaeoclimate, subsistence strategies, and culture are intertwined with variability in human interaction (Berger et al. 2019; Fyfe et al. 2019; Manning & Timpson 2014; Palmisano et al. 2017, 2019, 2021a, b; Shennan et al. 2013; Timpson et al. 2014; Warden et al. 2017; Weiberg et al. 2019; Wigand & McCallum 2017).

The majority of these methodological approaches aim to extract information on diachronic trends from large quantities of radiocarbon dates, and developed methods to mitigate problems caused by their inherent uncertainty (Bevan & Crema 2021a). Part of these studies, especially those focusing on western Asian contexts, adopt a multiproxy approach in which they compare various archaeological and palaeoecological sources of information (Lawrence et al. 2021a; Palmisano et al. 2021b). While these methods are informative and critical for inferring potential processes of interest, quantifying demographic trends using archaeological proxies (including ^{14}C dates) presents methodological challenges and theoretical assumptions that vary depending on the chosen variables.

All methods assume a proportional relationship between the density of a given type of archaeological evidence, measured at the chosen temporal and spatial scale, and the relative (rather than absolute) intensity of human activity/occupation in the same study area at the chosen temporal resolution (Drennan et al. 2015). However, all archaeological variables are inherently affected by taphonomic processes, loss of information with increasing temporal depth (Brantingham et al. 2007), biases in research design, intensity, and resources, specific levels of uncertainty and error, potential temporal/spatial mismatches in their respective scales of analysis (French & Collins 2015; Müller & Diachenko 2019), uncertainty linked to modifiable archaeological units and processes of dispersal (Crema & Bevan 2021), and differences in scope and spatiotemporal sampling resolution (Perreault 2020). Additionally, many assumptions, such as uniformitarianism, are often implicitly accepted (French et al. 2021).

Examples of adopted archaeological proxies include site counts, site size, stratigraphic information, genetic effective population size, bioarchaeological demographic profiles (Bocquet-Appel 2002), carrying capacity, palaeoenvironmental and palaeoecological data, and summed probability distributions of radiocarbon dates (French & Collins 2015; French et al. 2021). For regional datasets, mostly consisting of survey data, site counts, and site extension are often readily available sources of information. However, site counts alone are particularly susceptible to biases in research intensity, taphonomy,

and chronological uncertainty due to surface findings. Additionally, the assumption of a linear relationship between settlement size and population density may not always hold across periods or contexts ([Palmisano et al. 2017](#)).

1.2 PROBABILISTIC APPROACHES TO ARCHAEOLOGICAL RESEARCH IN WESTERN ASIA

Recent research efforts have focused on reconstructing demographic fluctuations in Near Eastern archaeological contexts using probabilistic methods, specifically aoristic approaches. These approaches aim to address the chronological uncertainty inherent in archaeological proxies and to make different sources of information directly comparable at the chosen temporal resolution (e.g., [Lawrence et al. 2021b](#); [Palmisano et al. 2021b](#)). The aoristic method estimates the intensity of events over time by standardizing the temporal units of analysis across the entire study period, a technique already widely applied in various archaeological contexts ([Bevan et al. 2013](#); [Crema 2012](#); [Johnson 2004](#); [Orton et al. 2017](#); [Palmisano et al. 2017](#); [Ratcliffe 2000](#); [Romandini et al. 2020](#)). This approach is based on two primary assumptions. First, the total probability of observing the occupation of an archaeological site during the temporal interval of a specific cultural phase is 1. This means that the site is certainly occupied within the archaeologically determined chronological interval. Second, in the absence of more detailed information, it assumes a uniform probability of existence or occupation of the site throughout the entire time interval of the cultural phase. Thus, if the temporal length of a cultural phase is divided into equal time blocks (e.g., 100-year bins), each block has an equal fraction of the total probability of existence, known as its aoristic weight. The relative aoristic weight depends on both the total temporal length of the cultural phase and the width of each time block. Applying this method across all sites allows for the summation of the aoristic weight of each site or event per time block, resulting in an aoristic sum that produces a long-term time series estimating the intensity of human occupation over time.

Although this method addresses some issues of uncertainty in the archaeological record, it is still susceptible to biases related to the dating precision of different cultural phases based on surface findings, the inherent limitations of the dating techniques themselves, and the lifespan of the most diagnostic artifacts for each phase. To mitigate these issues, further implementation of Monte Carlo methods is necessary. These methods simulate random start dates and site durations based on theoretical or empirical prior probability distributions, generating a probability envelope of existence. This approach accounts for the likelihood that the lifespan of most sites would be shorter than the entire duration of a cultural phase ([Lawrence et al. 2021a, b](#); [Palmisano et al. 2017](#)).

Recent critiques have highlighted the limitations of the aoristic method, particularly regarding the summation of aoristic weights, the influence of archaeological periodization, and its reliance on descriptive rather than inferential statistics ([Crema 2025](#)). Despite these concerns, aoristic analysis remains a widely used and valuable approach for exploring archaeological patterns in datasets where absolute dating is limited or unavailable. Its main strengths and limitations are discussed in Section 2.2 of the Materials and Methods.

1.3 SUMMARY OF THE PRESENT RESEARCH

We contribute to this research agenda by reconstructing prehistoric population changes in the eastern portion of Southern Arabia between the Late Pleistocene and the beginning of the Late Holocene (10,000 and 3,000 cal. BCE; [Figure 1](#)). In this paper, when commenting on graphs and comparing datasets, we use dates in BCE (Before the Common Era) rather than BP (Before Present) for consistency and ease of comparison across archaeological and palaeoclimatic records, even when analyses were conducted using BP dates. This decision aligns with the convention in most Neolithic literature, making it easier to navigate and compare our findings with existing research.

This study draws on a large corpus of archaeological data including projectile points from excavations and surveys, radiocarbon dates, and palaeoclimatic records to provide a long-term empirical analysis at a regional scale (e.g. [Maiorano et al. 2020a](#); [Böhner & Schyle 2006](#); [Shah et al. 2013](#)). The assumption is that increased aridity will negatively affect soil moisture, vegetation, food production, and human population, although this relationship is mitigated by human responses such as social and technological adaptation, and population movement ([Palmisano et al. 2021b](#)). Initially, we preferred to rely exclusively on charcoal-based radiocarbon dates to maintain consistency and avoid the complex reservoir effects associated with bone or marine shells. However, restricting our analysis to charcoal would have significantly reduced the size and representativeness of our dataset, so we expanded our selection of radiocarbon dates to include those obtained from marine shells, which often represent the only available samples from coastal archaeological sites excavated over the past 40 years.

To date, this is the largest collection of radiocarbon dates for the Early and Middle Holocene in this region. Southern Arabia is characterized by diverse landscapes and climate regimes, with extremely dry conditions prevailing with the exception of southern Dhofar, where precipitation is increased by the Indian Monsoonal system ([Zerboni et al. 2020](#)). Despite efforts to ensure spatial and temporal congruence between demographic and climatic records, this has not always been possible due to the distribution of palaeoclimate records and archaeological data.

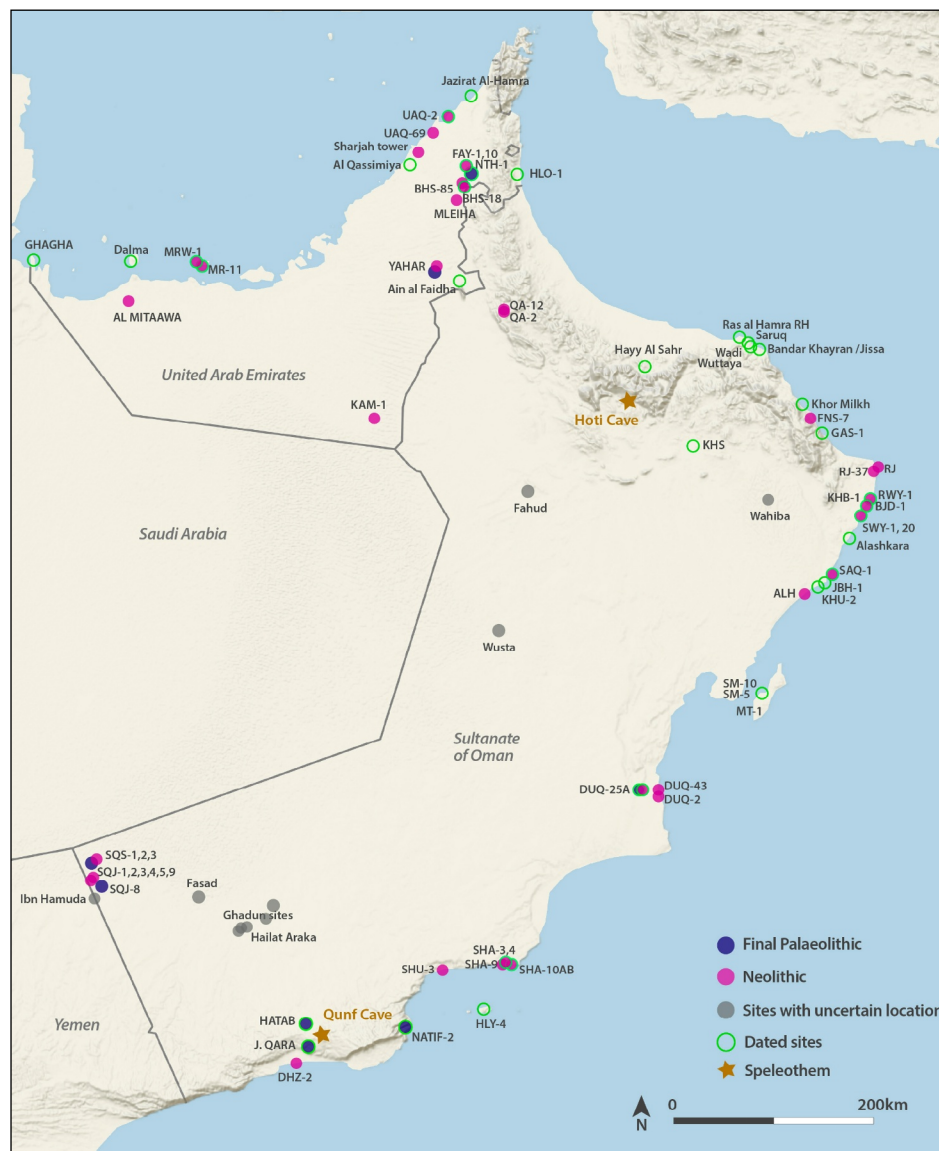


Figure 1 Map of the Final Palaeolithic and Neolithic sites in modern Oman and the UAE. Pink and blue dots indicate sites with projectile points and verified location, while grey dots represent sites where projectile points are present, but their geographical location is approximate. The green circle marks the dated sites included in this study. Dark orange stars indicate the location of speleothems. Map by M. P. Maiorano.

2. MATERIALS AND METHODS

The dataset includes 662 entire and partially complete projectile points from 53 sites and 346 radiocarbon dates from 84 sites (See the dataset “S1 data” and “S2 dates_om_uae_clean” in Supplementary Materials). The artefacts belong to the collection of the Ministry of Heritage and Tourism of the Sultanate of Oman and the Al-Ain Museum in the UAE (Maiorano 2020), incorporating both published and unpublished data, as well as illustrations from published articles and recent excavations conducted in Oman (e.g., Al-Khashbah, Maiorano et al., 2025a; Maitan in the southern Rub al Khali, Maiorano et al., 2020b; Wadi Sayy DUQ-25A in Duqm). The analysed samples are part of a larger corpus of 1200 projectile points (that included fragmented specimens) systematically described using 72 metrical, morphological, and technological analytical units (Maiorano 2020; Maiorano et al., 2020a). All continuous

variables (e.g., maximum medial thickness, outer angle spread sum, etc.) were transformed into discrete variables (represented by integer values) to facilitate data management. Intervals were determined using descriptive statistics, and the variables were subsequently binned into four or five classes (Table 1). To streamline the classification process, we selected 15 out of 72 characters based on previously calculated PCA loadings (for further details on this approach, see Maiorano et al., 2020a). The assemblage was further enlarged by adding 112 points preserving the medial-basal portion to the 550 complete projectile points, as this portion of the point often preserves the essential features needed to identify the production technology and most stylistic attributes (Maiorano 2020). However, by including medial-basal fragments, some metric variables, such as apical section, apical thickness, and the ratio between apical and medial widths, had to be excluded (Table 1; Figure 2).

CODE	CHARACTER	CHARACTER STATES
<u>MTH</u>	Maximum thickness of the medial part (Figure 2)	1–1.5 < × < 3.7 2–3.8 < × < 4.5 3–4.6 < × < 5.5 4–5.6 < × < 8.2 5– > 8.3
<u>OutAng</u>	Outer angles spread sum (Figure 2)	1–140 < × < 240 2–241 < × < 276 3–277 < × < 307 4– × > 308
<u>Msec</u> and <u>Bsec</u>	Medial section and Basal section	1 trihedral 2 plano-convex 3 biconvex 4 romboidal 5 blank (unretouched) 6 irregular (inconsistent retouched)
<u>APX</u>	Presence of wings or different appendixes	1 wings (>4 mm long) 2 “ears” (<4 mm long) 3 denticulation 4 tang tips (hollow based point) 5 long wings (L ≥ tang length) 6 “ergot” (squared/sub-squared) 0 absence
<u>ShD</u> and <u>ShV</u>	Dorsal Shaping Symmetry and Ventral Shaping Symmetry	1 symmetric 2 asymmetric 3 from one side 4 mixed 5 fluted 0 not retouched
<u>RTECH</u>	Retouch technique	1 pressure 2 direct 3 direct on anvil 4 mixed
<u>BLK</u>	Blank	1 flake: LW < 1.79 2 flake-blade: 1.80 < LW < 2.79 3 blade: LW > 2.80 4 unknown
<u>III_R_pos</u> and <u>VII_R_pos</u>	Retouch position on the third and seventh sub-square	1 direct 2 inverse 3 alternate 4 alternating 5 crossed 6 bifacial 0 absent
<u>III_R_ext</u> and <u>V_R_ext</u>	Retouch extension of the 1st sub-square	1 short 2 long 3 covering 0 absence
<u>V_R_delin</u> and <u>VII_R_delin</u>	Retouch delineation on the first sub-square	1 rectilinear 2 convex 3 concave 4 notched 5 denticulated 6 serrated 7 convex shoulders 8 concave shoulders 9 notched concave shoulders 10 winged shoulders 11 crossed shoulders 12 notched convex shoulders 13 “ergot” shoulders 0 absent
Total: 15 Characters, 61 Character states		
Total number of analysed points from Oman and UAE: 662		

Table 1 List of selected characters and modes.

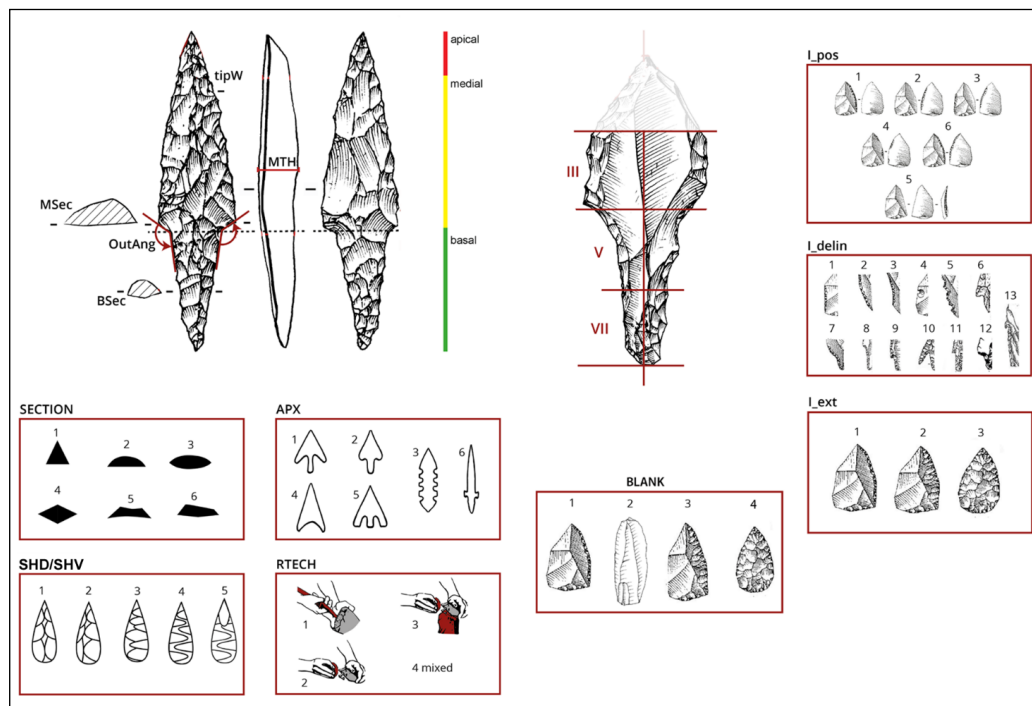


Figure 2 Characters and modes listed in Table 1. To reduce noise and fit the classification scope, 15 characters were selected based on PCA loadings. These characters effectively capture variability within the points' distribution.

2.1 CORRESPONDENCE ANALYSIS AND MULTIPLE CORRESPONDENCE ANALYSIS

Correspondence Analysis (CA; [Greenacre 1984, 1993](#)) and Multiple Correspondence Analysis (MCA; [Abdi & Valentin 2007](#)) were used to identify clusters within the projectile point data. CA analyses relationships between categorical variables by representing the data in a lower-dimensional space, helping visualize patterns and relationships among different variables. MCA extends this method to multiple categorical variables, allowing for the identification of patterns and clusters within the data. These techniques revealed distinct clusters of projectile points, corresponding to different technological and cultural practices.

To explore the underlying structure and identify groups within the data, various clustering methods were applied to the MCA results. First, Euclidean distances between individual coordinates from the MCA were computed, followed by hierarchical clustering with Ward's method ([Ward 1963](#)), which minimizes the total within-cluster variance. Next, K-means clustering was applied to the MCA coordinates, setting the number of clusters to 12 to minimize the total within-cluster variance ([Hartigan & Wong 1979](#)). The clustering results indicated that these clusters explained 70% of the total variance.

Additionally, we performed CA on the contingency table of the K-means clusters and the technological variable from the original dataset to get further insight and understanding of the clustering results. We integrated K-means cluster assignments into the original dataset (column: CLUSTER) for subsequent analyses (see "S3 data_newclusters" in the Supplementary Materials).

2.2 AORISTIC ANALYSIS

Aoristic analysis is a technique used to generate time-series data from the occurrence of chronologically mismatching or partially overlapping events. It therefore helps accounting for temporal uncertainty and potential biases due to differential research intensity ([Bevan et al. 2013](#); [Crema 2012](#); [Johnson 2004](#); [Orton et al. 2017](#); [Palmisano et al. 2017](#); [Ratcliffe 2000](#); [Romandini et al. 2020](#)). This method involves assigning a start and end date to each archaeological event of interest and dividing the entire study period into fixed-width time bins (200-year intervals in this case). Using fixed temporal intervals offers significant advantages, such as facilitating comparisons between pairs of bins and among estimated trends using different proxies (like climatic or environmental data). At the same time, in the absence of more precise or independent chronological information for the use of the identified objects or clusters, a fixed temporal resolution allows us to straightforwardly adopt a uniform probability distribution as the best approximation for the use of a specific technological taxon or unit. By dividing the total probability mass of existence of each object, trait, or cluster (equal to 1) across the time bins falling in its respective temporal interval (t), the probability of observing a particular object, trait, or cluster at each bin is calculated as $1/t$. Each bin will therefore contain a fraction of the total probability. Summing all the fractions calculated for all objects, traits, or clusters falling into the same bin, and repeating this process for the entire study period, provides an estimate of the frequency distribution of objects, traits or clusters which effectively incorporates temporal uncertainty, and biases present in the data.

Following Palmisano et al. (2019), we created 200-year time blocks, updating each with individual site start and end dates. Site counts and aoristic weights were then computed, providing a time-block proportional count and uniform probability of existence across all time blocks for each site (full code available as “S4 Codes_Maiorano_Bortolini” in the Supplementary Materials).

Next, we calculated the aoristic sums for each technological cluster and computed the relative aoristic weights for each cluster. We then estimated diversity at each temporal bin using Hill’s numbers (effective number of species) based on Simpson’s concentration index, to better control for the effect of rare classes (Hill 1973). We summarised all data by calculating the total site counts and aoristic weights for the entire study period and then normalised all the proxies to facilitate comparison.

Limitations of the aoristic approach and rationale for its use

Although aoristic analysis is now a common solution to visualise chronological uncertainty in archaeological datasets, it presents well-known theoretical and practical limitations. For example, it violates the axioms of probability theory when uniform probabilities are summed across events, often generating misleading representations of temporal intensity (Crema 2012) and spurious peaks at cultural-phase boundaries (Bevan & Crema 2021a). Moreover, the method is descriptive rather than inferential and does not directly test alternative demographic or cultural hypotheses (Crema 2025).

Despite these issues, its transparency and minimal parameterisation make it particularly suitable for exploratory analyses of sparse and heterogeneous data. Since no robust priors exist for the present case study to constrain recently proposed Bayesian alternatives (Crema 2025), and chronological information for individual artefacts is highly uncertain, we retain the aoristic framework as a first-order descriptive model, which allows us to explore for the first time technological trends in the region and to compare them directly with demographic and climatic proxies.

2.3 SUMMED PROBABILITY DISTRIBUTION

Summed Probability Distribution (SPD) was applied to calibrated radiocarbon dates to infer population dynamics over time. This method sums the probability distributions of individual radiocarbon dates to create a composite probability distribution representing changes in population density over time (E.g. Shennan et al. 2013; Crema et al. 2016). The obtained SPD was compared against theoretical null models (in this case a logistic one) to identify significant deviations pointing to possible demographic changes.

The demographic proxies were calculated from a dataset of 346 radiocarbon determinations, comprising balanced subsets of shells ($n = 171$) and charcoal or

charred wood ($n = 175$). Calibrations were performed in R v.4.5.2 (R Core Team 2025) using the rcarbon package (Crema & Bevan 2021; Bevan & Crema 2021b). Terrestrial samples were calibrated using the IntCal20 curve (Reimer et al. 2020) while marine shells were processed with the Marine20 curve (Heaton et al. 2020) using a regional $\Delta R = 163 \pm 51$ ^{14}C yr derived from RH-6, Muscat (Zazzo et al. 2016). We used unnormalised calibrations (Weninger et al. 2015) to limit artificial peaks and applied spatial-temporal binning to counteract wealth and sampling biases.

Because the distribution of dates is uneven, we explored several bin widths using the binsense() function. Sensitivity tests (100–500 yr; Figure 8A) showed that the overall SPD shape is stable across scales, and we therefore adopted 200-year bins, which offer a balance between chronological resolution and data density.

The SPD for each calibrated date was generated using the spd() function over the period relevant to our study (12,000–4000 BP/10,000–2000 BCE). To fit a demographic model, we used a logistic function, starting with adjusted values based on observed SPDs. We employed non-linear least squares (nls) to fit the model, generating predicted SPD values. The model’s fit was evaluated using the modelTest() function, with the logistic model demonstrating a significant global fit ($p < 0.001$).

To correct for taphonomic loss over time, we applied the exponential correction proposed by Surovell et al. (2009) using the transform SPD() function in rcarbon. Comparison between corrected and uncorrected curves shows identical trends, with the expected enhancement of older peaks. Consequently, the corrected SPD was used for subsequent analyses.

As an independent check, a composite Kernel Density Estimate (ckDE; Brown 2017) was produced with the ckde() function (Figure 9A). Its smoother trajectory closely follows the SPD trend, confirming that the observed demographic oscillations are not artefacts of calibration noise. Additional SPDs calculated separately for shell and charcoal samples further confirm internal consistency between marine and terrestrial subsets, while showing a differential distribution of sampled materials across the studied sites (Figure 9B).

2.4 CORRELATION WITH ENVIRONMENTAL PROXIES

We examined the correlation between technological aoristic sums, demographic proxies, and palaeoenvironmental data, specifically stable oxygen isotope ratios ($\delta^{18}\text{O}$) as proxies of relative precipitation levels. In arid and semiarid contexts, these ratios correlate with available biomass and water (Jones et al. 2019), facilitating comparability with previous macro-regional results (Palmisano et al. 2021b). However, groundwater resources, both fossil aquifers and those recharged by precipitation, also play a crucial role in supporting

vegetation and sustaining human occupation. Future analyses should therefore incorporate these additional hydrological proxies.

Higher $\delta^{18}\text{O}$ values indicate drier conditions, while lower values suggest wetter climate. However, other factors such as evaporation, vegetation, and air mass trajectories can influence this sensitive proxy, especially in semiarid regions (Baker et al. 2019). In addition, oxygen isotopes from speleothems may be biased by winter precipitation rather than annual averages (e.g., Bini et al. 2019). The selected proxies were derived from Hoti Cave (57.35 N, 23.08 E, Neff et al. 2001) and Qunf Cave (54.18 N, 17.1 E, Fleitmann et al. 2007; Shah et al. 2013) (see “S5 hoti” and “S6 qunf” in the Supplementary Materials). Following Palmisano et al. (2021a, b), we selected temporal intervals that overlapped with the archaeological patterns of interest and binned the z-scores of these records into 200-year blocks to make them directly comparable with demographic and technological proxies. The resulting diachronic trends were plotted alongside demographic and technological proxies to explore potential relationships among them. The latter were also globally ascertained through pairwise Spearman correlation coefficients, due to lack of normality and the presence of a linear relationship among the examined trends.

To explore short-term coupling and decoupling between demographic and climatic trends, we applied a moving-window Pearson correlation between the corrected SPD and the $\delta^{18}\text{O}$ records from Qunf and Hoti

caves. The method follows Palmisano et al. (2021b) and computes correlations over 500-year windows shifted in 50-year steps. This approach identifies transient phases of synchrony or divergence that may be masked in whole-series comparisons. All time series were resampled at 50-year intervals, z-scored, and compared using Spearman correlation coefficients. (datasets: S9 movingWin_Hoti.csv, S10 movingWin_Qunf.csv in Supplementary Materials).

Correlation coefficients (ρ) range between -1 and $+1$, where positive values indicate parallel trends (i.e. population growth during wetter conditions, indicated by lower $\delta^{18}\text{O}$ values) and negative values denote opposite trajectories, i.e. demographic expansion under increasing aridity. Together, these procedures enabled a comprehensive exploration of population dynamics, technological change, and their relationships with climatic fluctuations in Southern Arabia during the Holocene.

3. RESULTS

3.1 CA AND MCA

After determining the optimal number of clusters via K-means and MCA ($n = 12$), we integrated these clusters into the dataset (S3 data_newclusters in Supplementary Materials). To explore the relationship between these new groups and traditional techno-complexes we used CA (Figure 3). Laminar point clusters are on the left of Dimension 1, while bifacially retouched ones are grouped on

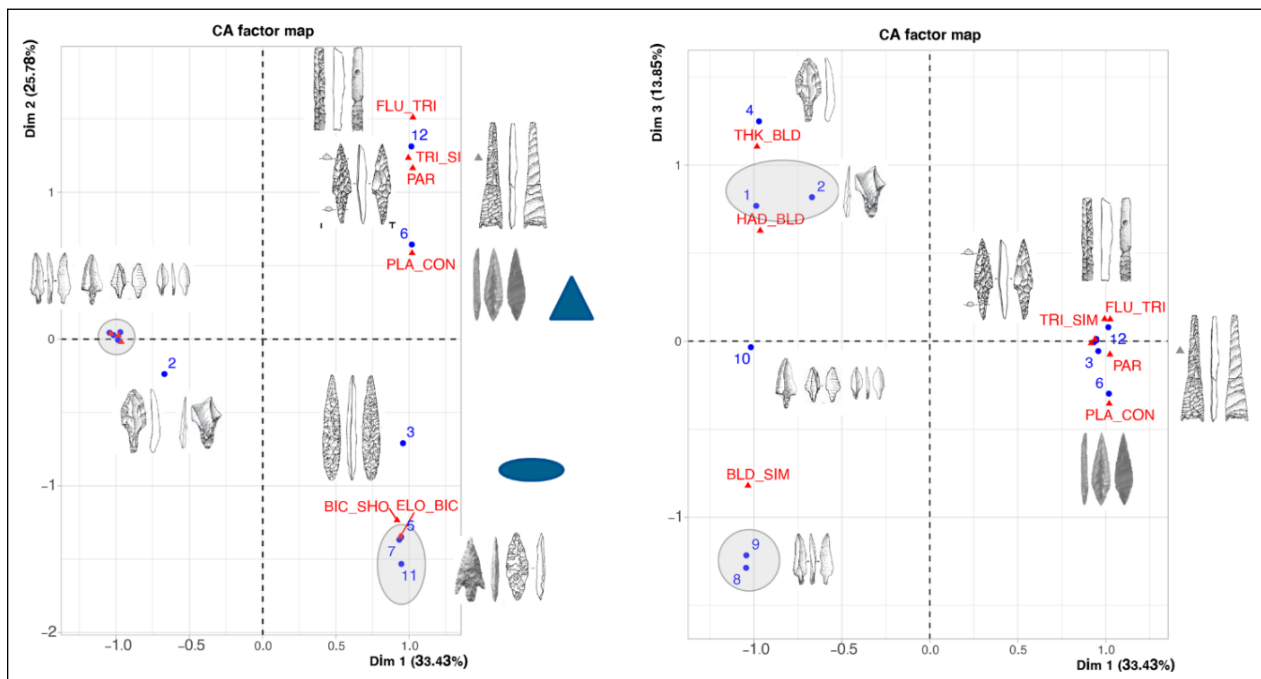


Figure 3 Distribution of projectile point clusters (blue dots) and traditional techno-complexes (red triangles) using Correspondence Analysis. The left graph (dimensions 1 and 2) better displays bifacially retouched point clusters. Fusiform points without lateral appendices and winged/barbed points are separated in the lower quadrant, while trihedral and planoconvex points are in the upper right quadrant. The variability of laminar points is further explored using the 1st and 3rd dimensions (on the right). Points from Sharbithat and Al-Haddah share the same space due to their thicker and larger blanks and higher invasivity of the retouch, whereas points from Natif, Faya, and Fasad are separated primarily by dimensional components. The grey ellipses show the merged clusters.

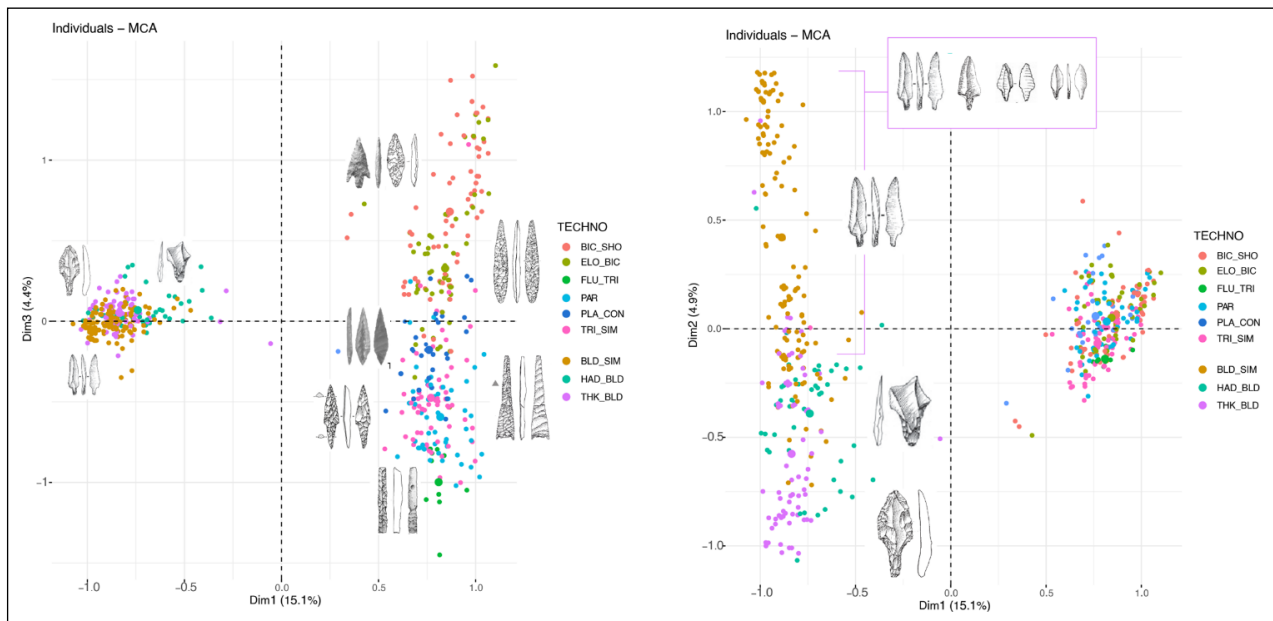


Figure 4 Visualization of projectile point distribution using Multiple Correspondence Analysis (MCA). The 3rd dimension reflects the distribution of bifacial points (left), the 2nd dimension shows laminar points (right), and the 1st dimension distinguishes the former from the latter. The distinction between these groups is not always neat, with overlaps corresponding to less standardized groups and more hybrid forms.

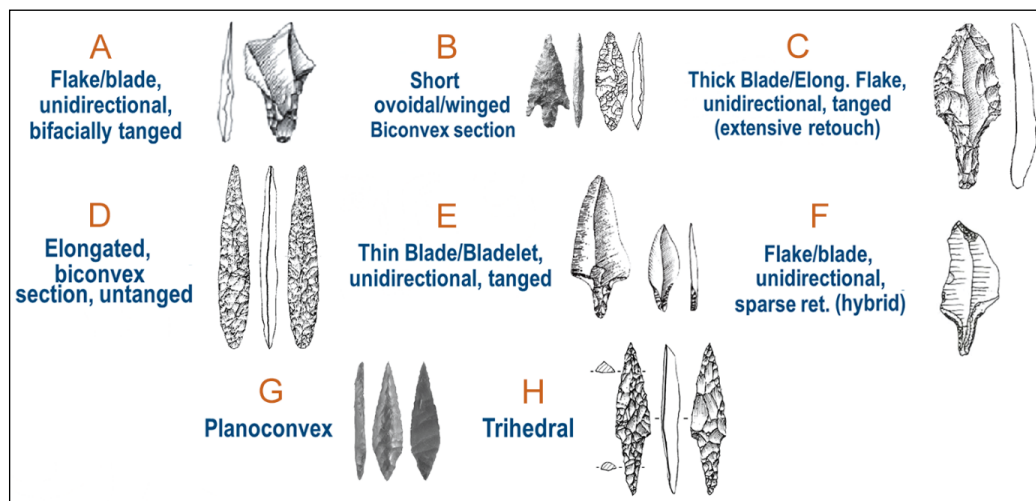


Figure 5 The newly identified eight clusters (from A to H), reflecting the main techno-complexes.

the right. The bifacial points graph separates fusiform points without lateral appendices and winged/barbed points in the lower quadrant from trihedral and planoconvex points in the upper right quadrant. To further explore the variability in laminar points, we used the 1st and 3rd dimensions (Figure 3, graph on the right), revealing that points from Sharbithat (THK_BLD, Fig. 3) and Al-Haddah (HAD_BLD, Fig. 3) share the same space, indicating thicker and larger blades with significant retouch impacts. In contrast, points from Natif, Faya, and Fasad (BLD_SIM, Fig. 3) are separated primarily by dimensional components. For more information on the names used to identify projectile points, see the “S12 Basic_Terminology” file in the supplementary materials.

MCA visualised the distribution of single points within clusters (Figure 4), showing how individual points distribute within the new groups, with some overlaps and

hybrid forms indicative of cultural exchange, possible copying error processes, and cultural variation within groups. We acknowledge that this lower percentage of total variance explained by the analysis indicates a more complex and nuanced dataset where the underlying patterns are less pronounced. As such, the interpretations based on this figure are presented with a clear indication of their exploratory nature and are used primarily to suggest potential trends and hypotheses rather than definitive conclusions. The CA and MCA results allowed further summarisation and merging of the least populated clusters with the closest ones (e.g., Cluster 8 with only 2 points was merged with Cluster 9; Figure 3) and given new names from “A” to “H” for a total of 8 final clusters (See the dataset “S3 data_newclusters” in the supplementary materials; Figure 5).

3.2 COMPARING FREQUENCY ESTIMATES AND DIVERSITY

Aoristic analysis and time-block proportional counting provided detailed insights into the temporal distribution of Final Palaeolithic and Neolithic points, and of their technological clusters. The temporal distribution of raw counts and aoristic sums closely matched, indicating a consistent pattern in the dataset. Relative Aoristic sums calculated for each technological cluster, on the other

hand, highlighted distinct temporal trends with different peaks and declines over time for each cluster (Figure 7).

The calculated diversity index (Hill's numbers) provided additional insights on the variability exhibited by technological clusters and on diachronic trends in regional variability.

During the Early Holocene (ca. 10,000–6500 BCE), a class of projectile points known as Fasad (cluster E, Figure 5E; Figure 6A; Figure 7) spread throughout the region. These

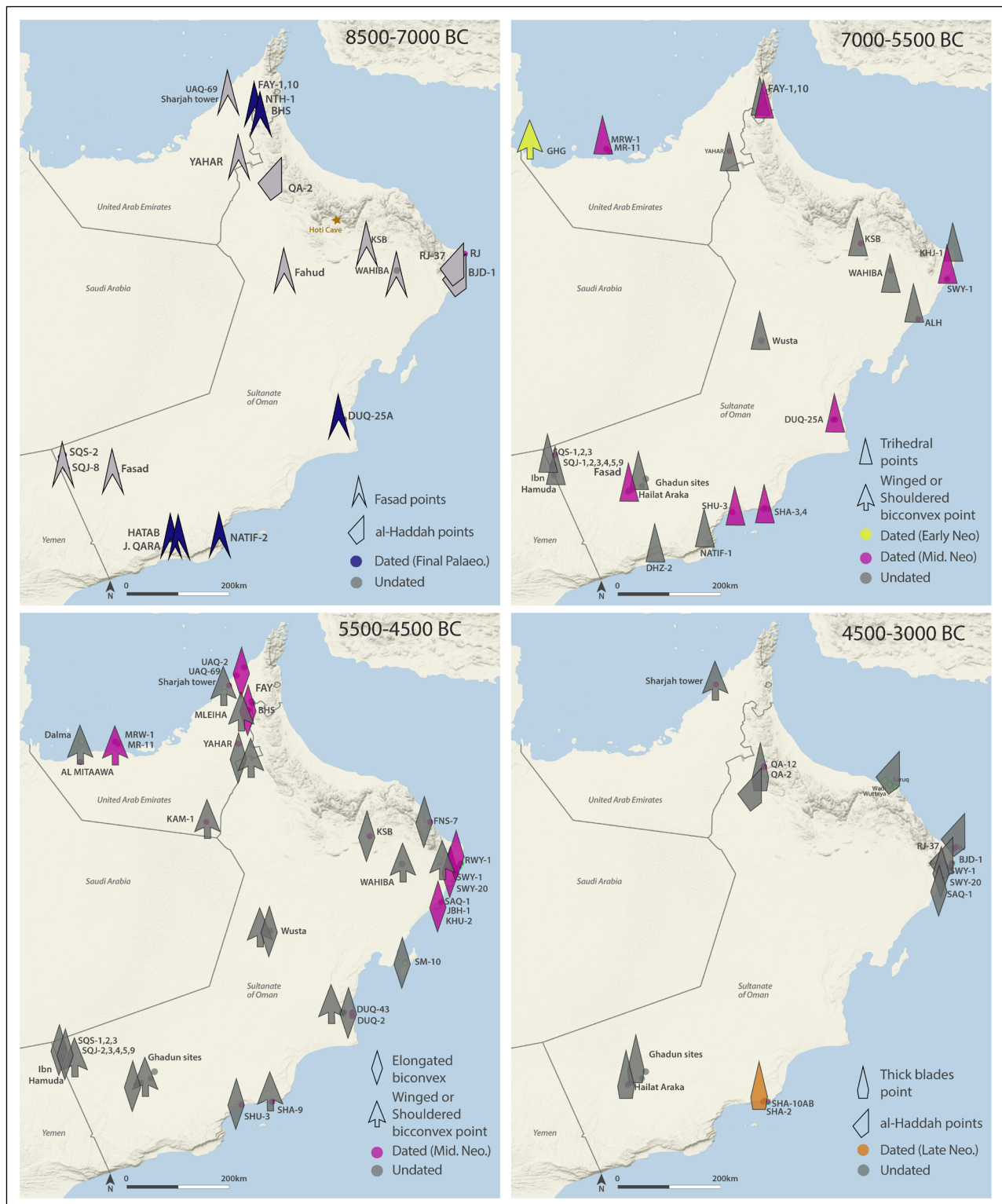


Figure 6 Spatial distribution of projectile point techno-clusters across the chronological windows discussed in the text.

points (cluster E) share similar production technology with Faya and Natif points, that clearly separates them from Wa'sha points in Yemen and bidirectional points found between the Levant and Qatar (for a complete discussion on the mentioned *facies*, see [Charpentier & Crassard 2013](#)). This cluster remained predominant until the 7th millennium BCE, despite the emergence of subregional variants, such as those seen in Faya and Natif ([Charpentier & Crassard 2013](#)). In this period, we observe high values in point counts, aoristic sums, and diversity. Alongside the more abundant Fasad points, Al-Haddah points also emerged across the Sharqiyah region in Oman, although their evidence remains at present undated (Cluster A, [Figure 5A](#); [Figure 7](#)). The technological similarities of Cluster A (Al-Haddah points) with both the Fasad points (Cluster E) and the chronologically younger Sharbithat points (Cluster C; [Figure 5C](#); [Maiorano et al. 2018](#)) result in an increase of their aoristic sum during two distinct intervals: first in the 9th–8th millennia BCE, and later in the 4th millennium BCE ([Figure 7](#)).

The 7th millennium BCE represents the phase of regional prehistory with the lowest number of securely dated sites. At present, the only published dated context is the Neolithic site of Ghagha Island ([Al-Hameli et al. 2023](#); [Crassard et al. 2023](#); [Figure 6B](#), “GHG”), which features domestic architecture and barbed projectile points with biconvex cross-sections comparable to those assigned to Cluster B ([Figure 5B](#)). However, Ghagha Island's distinct settlement strategies and its closer cultural and geographic connections to Levantine-influenced regions such as Qatar, rather than to Southern Arabia, limit its suitability as a representative reference for the present analysis.

The scarcity of securely dated evidence for this interval may therefore account for the apparent decrease in point numbers and the concurrent rise in

typological diversity, a pattern that could reflect either increased regional isolation or, more plausibly, research bias linked to small sample size. At the beginning of the 7th millennium BCE and throughout the 6th millennium BCE, diversity decreases while the total number of points increases. This pattern can be explained by the higher proportion of trihedral points (Cluster H, [Figure 5H](#); [Figure 6B](#); [Figure 7](#)) and points with planoconvex cross-sections (Cluster G, [Figure 5G](#)), likely influenced by the spread of knapping technologies first documented in Hadramawt, Yemen ([Crassard 2008](#)). From the end of the 7th through the 6th and into the first half of the 5th millennium BCE, both counts and variability in projectile technology considerably increased once again ([Figure 6C](#); [Figure 7](#)), as a result of the increase in the number of sites, which can be interpreted as indicative of a higher population density and a more intense human activity. At this stage, lithic technology reached a developmental peak, characterised by the emergence of new projectile point variants. These variants initially maintained a common technological basis, indicating an evolutionary adaptation within existing technological frameworks rather than the introduction of completely innovative traits. In the 5th millennium BCE, points with a biconvex section (Cluster B and D; [Figure 5B, D](#)), especially fusiform elongated points (Cluster D, [Figure 5D](#); [Figure 6C, D](#); [Figure 7](#)), became the most widespread. These points, however, were less common than trihedral ones, and seemed more prevalent in the UAE and central/northern Oman ([Charpentier 2004](#)). By the 4th millennium BCE, diversity increased again, projectile points began to disappear from most areas, and a trend toward greater localization was confirmed by the diffusion of Sharbithat points (Cluster C, [Figure 5C](#); [Figure 6D](#)) in some areas of Dhofar and similar, yet undated, specimens from inland sites like Qumayrah ([Białowarczuk & Szymczak 2019](#)).

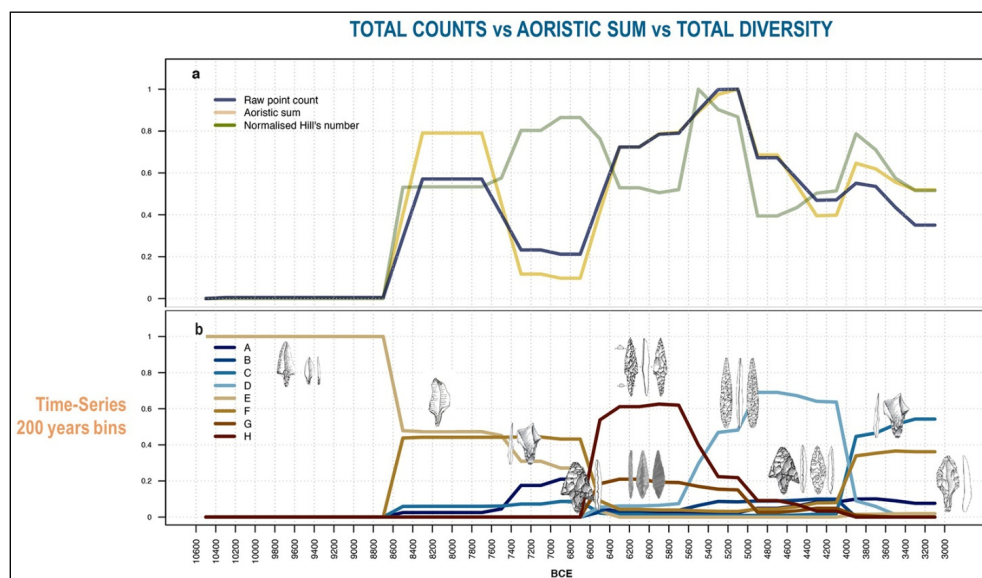


Figure 7 Total counts of projectile points over time compared with the aoristic sum and total diversity (a). The second graph shows the relative aoristic sums of each technological cluster, effectively presenting time-series distributions of points (b).

3.3 SUMMED PROBABILITY DISTRIBUTION OF RADIOCARBON DATES

The dataset used to compute summed probability distribution (SPD) comprises balanced subsets of shell samples ($n = 171$) and terrestrial materials such as charcoal and charred wood ($n = 175$). Sensitivity analyses testing bin widths between 0 and 500 years confirmed that the overall SPD shape remained stable across binning scales (Figure 8A). Larger bins amplified positive peaks, whereas smaller ones enhanced local minima, but none altered the general demographic trend.

The logistic model fit to the SPD data provided a strong predictive framework for understanding these trends (Figure 8B). The resulting curve follows a general rise-and-fall trajectory, with a gradual population increase beginning after 6000 BCE, reaching key peaks during the

5th millennium BCE, and declining thereafter through the 4th millennium BCE. Particularly notable are the statistically significant peaks around 4700 and 4400 BCE, which indicate possible phases of heightened population density. The absence of a null-model envelope before 6000 BCE results from the limited and uneven distribution of radiocarbon determinations for the earliest part of the record. Because the `modelTest()` function in the `rcarbon` package requires a minimum number of dated samples to simulate expected values, the sparse early data prevented reliable computation of the null model for that interval without introducing excessive uncertainty.

We applied the taphonomic correction proposed by Surovell et al. (2009) to control for the uneven preservation of datable materials. This yielded a corrected SPD nearly identical in shape to the uncorrected version, except for

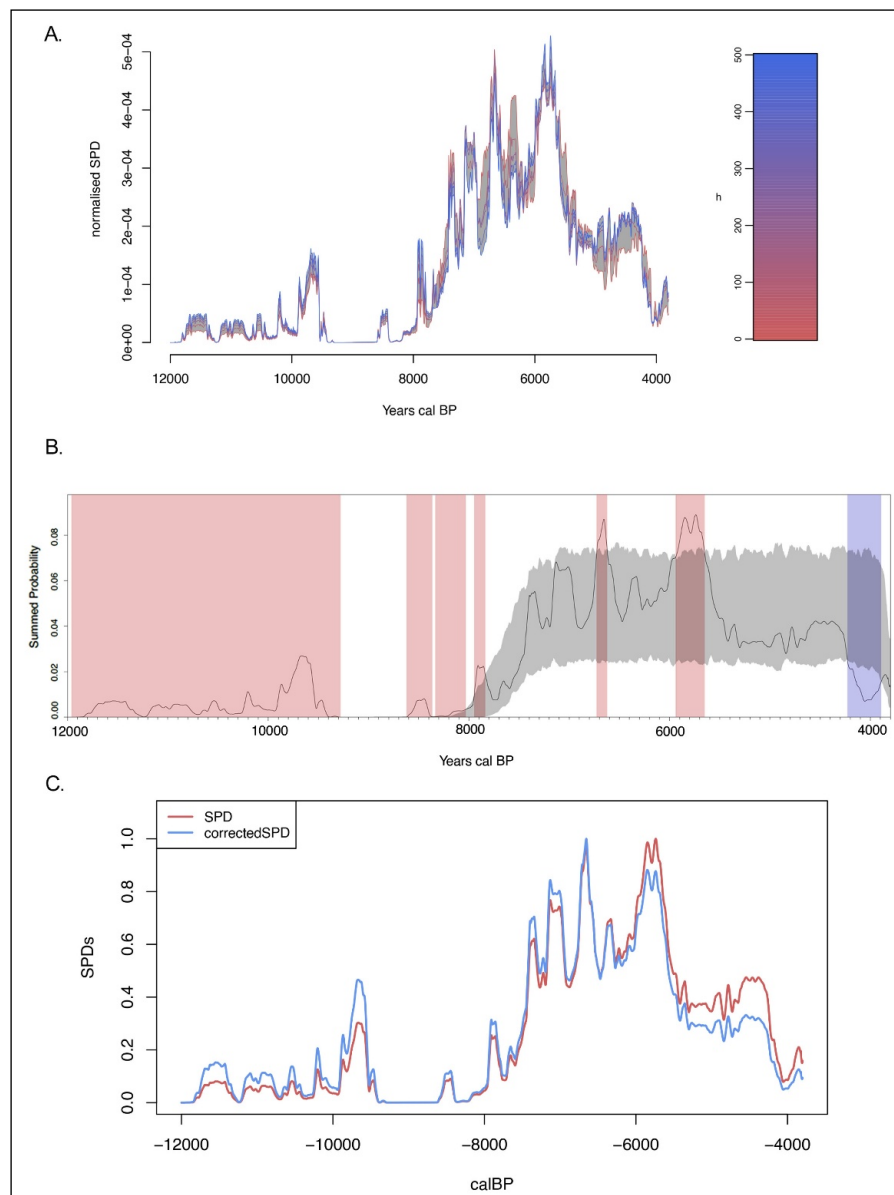


Figure 8 (A) Bin-sensitivity analysis with SPDs using 100–500 yr bins, showing stable overall trends. (B) Summed Probability Distribution (SPD black line) of normalized calibrated radiocarbon dates. Blue and red bands indicate chronological ranges where SPD deviates negatively and positively from the null model (95% confidence grey envelope). (C) Taphonomic correction following Surovell et al. (2009), with corrected and uncorrected SPDs displaying closely matching trends.

the expected enhancement of earlier peaks and mild attenuation of recent ones (Figure 8C). Given this close correspondence, the corrected curve was used for all subsequent analyses.

To assess the robustness of these demographic trends, we also generated an independent composite Kernel Density Estimate (cKDE; Brown 2017) using the `ckde()` function in `rcarbon`. The resulting curve mirrors the SPD trajectory, although with smoother oscillations and greater uncertainty between 6500 and 4500 BCE (Figure 9A). This convergence between the output of SPD and cKDE supports the reliability of the observed long-term demographic fluctuations.

Finally, separate SPDs were calculated separately for shell and charcoal samples (Figure 9B). The comparison confirms the internal consistency between the marine and terrestrial subsets, while also highlighting minor differences. The charcoal-based curve displays more pronounced peaks between 6000 and 3600 BCE, whereas the shell-based curve indicates a slightly later demographic increase, peaking around 3800 BCE. This offset likely reflects the uneven distribution of inland versus coastal sites, as well as the disproportionate reliance on shell samples for dating coastal contexts.

3.4 COMPARING DEMOGRAPHIC AND CLIMATIC TRENDS

The demographic proxies derived from the SPDs were then compared against palaeoenvironmental proxies from the Hoti and Qunf cave records, which have been already widely used in the literature as indicators of climatic instability and aridification in the region (Neff et al. 2001; Shah et al. 2013). By plotting these proxies together (Figure 10), we visually explored potential relationships between demographic changes and climatic variability. Figure 10 integrates corrected SPD, the mean cKDE curve, raw point counts, and the normalised Hill's diversity index. Pairwise Spearman correlations between demographic and environmental proxies reveal distinct regional patterns in the relationship between population dynamics and climatic variability (Tables in Figure 10; S7 and S8 in the Supplementary Materials). Correlations with the Hoti Cave record are weak and inconsistent, suggesting that demographic trends in northern Oman were only marginally influenced by local climatic oscillations. In contrast, the Qunf Cave record from southern Oman, which is more directly affected by the Indian Summer Monsoon, shows moderate positive correlations with both point counts and technological

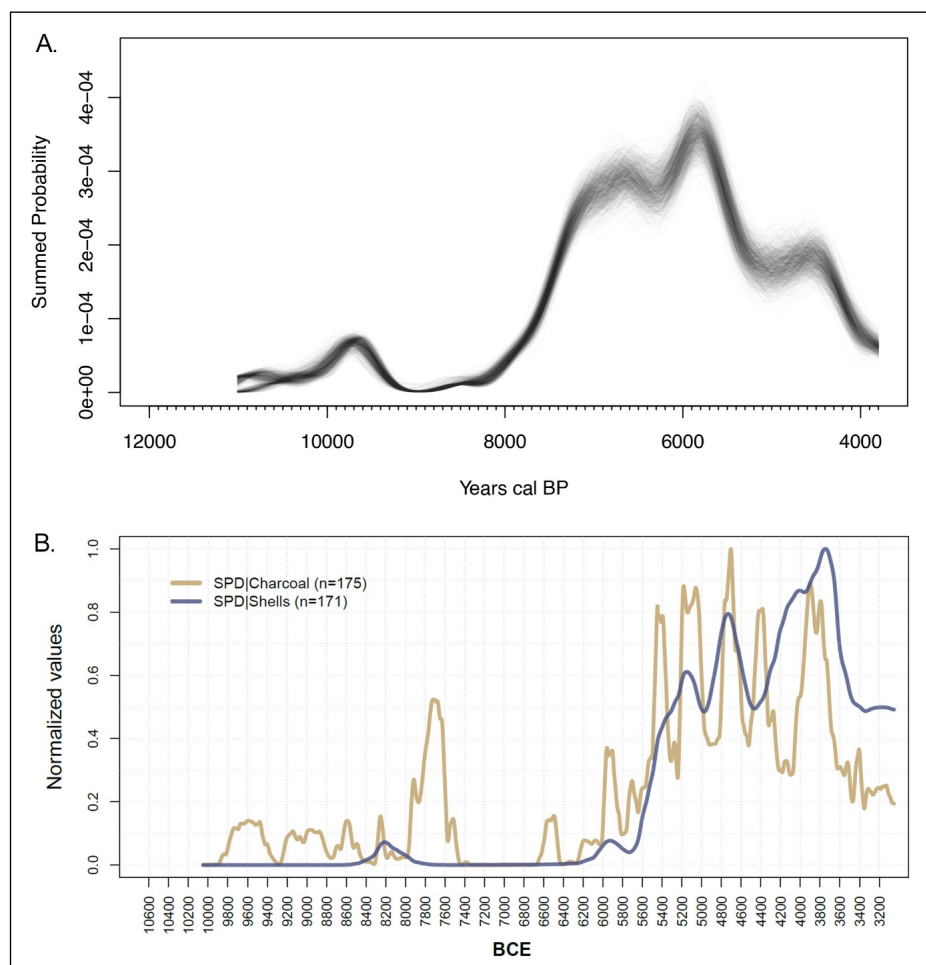


Figure 9 (A) cKDE (Brown 2017) providing an independent, smoother density estimate with comparable long-term patterns. **(B)** Separate SPDs for charcoal and shell samples, displaying consistent temporal trends despite different reservoir and taphonomic histories, confirming that demographic patterns are not driven by sample-type biases.

diversity, indicating a closer coupling between human activity and periods of enhanced humidity.

To refine these observations, we also applied moving-window correlation analyses to evaluate how the relationship between climate and demography may have varied through time (S9 and S10 in the Supplementary Materials). These temporally resolved correlations highlight a marked contrast between the two speleothem archives. For Hoti Cave, correlation coefficients fluctuate substantially between positive and negative values across adjacent windows, and no sustained intervals of agreement emerge among SPD, point counts, or Hill's numbers. This instability suggests that any apparent associations with Hoti represent short-lived fluctuations rather than persistent demographic responses to local climatic variability. Conversely, correlations with the Qunf Cave record form more coherent patterns: a cluster of strong positive correlations is present during the Early Holocene, and several moderate positive intervals occur throughout the Middle Holocene, particularly for SPD and point counts. Although correlations weaken in later windows, the overall pattern indicates longer periods of synchrony between demographic intensity

and phases of enhanced monsoon precipitation. These results complement the global Spearman coefficients by showing that possible links between climate and population growth in Southern Arabia were episodic rather than consistent and supporting the hypothesis that southern regions exhibit longer phases of alignment with monsoonal humidity.

Turning more specifically to palaeodemographic proxies, results suggest that, in the examined portion of Southern Arabia the local population experienced substantial changes from the Early to the end of the Middle Holocene, which may have been linked to climatic trends especially in southern Oman (Figure 10). Between 9800 and 7500 BCE, there was a general rise and fall in population, with a substantial increase between 8000–7600 BCE. This phase of population growth corresponds to improved climatic conditions indicated in the Qunf Cave record and is also attributed to a higher number of dated sites and projectile points (Figure 10).

After this marked boom in population density and human activity, results show a decrease in population proxies which corresponds to a drier period between 7400 and 7200 BCE (Figure 10). Despite the climatic

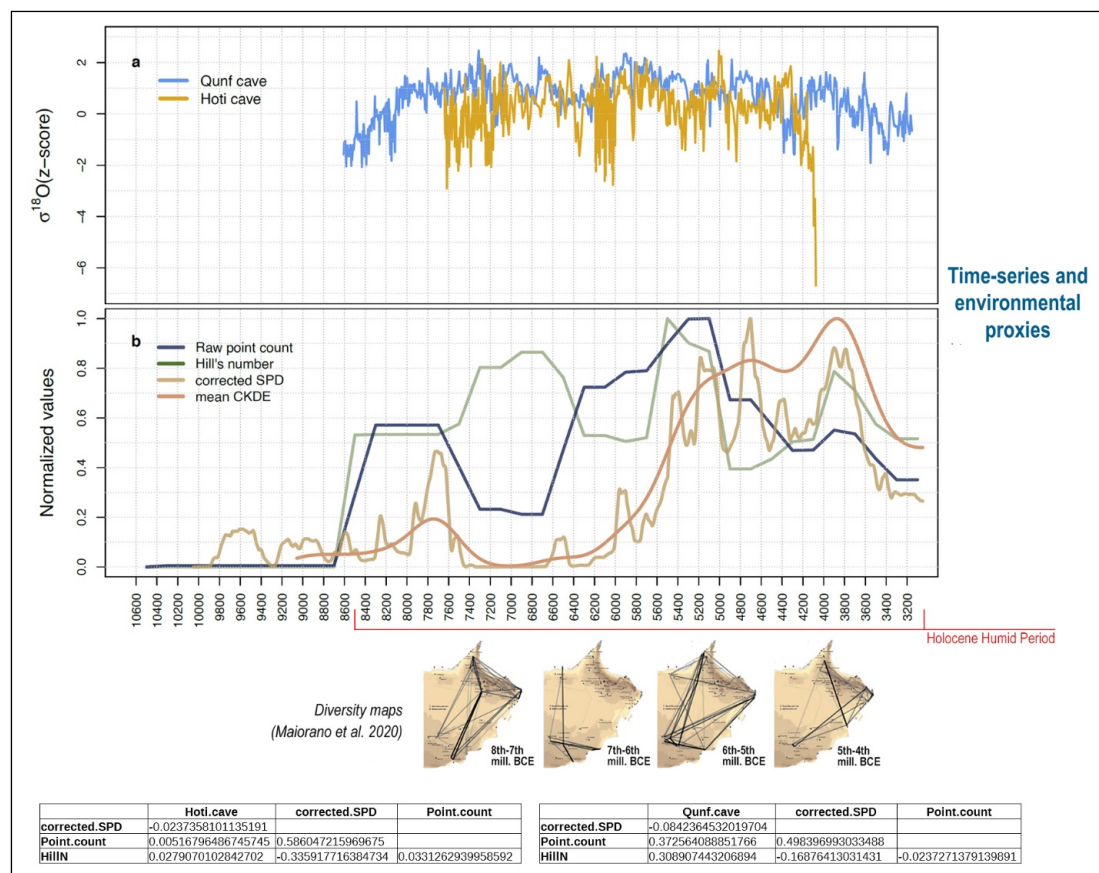


Figure 10 Comparison of point counts, technological diversity, demographic, and climatic proxies. After generating the SPDs, we compared demographic trends with environmental variability using the z-scores of the Hoti and Qunf cave speleothem records (Palmisano et al., 2021b), which serve as proxies for climatic instability and aridification. All proxies are plotted as time-series to visualize potential covariation through time. Furthermore, looking at the diversity maps (bottom), which show pairwise inter-site similarity as a measure of interaction (published by Maiorano et al., 2020a), we observe that population increase coincides with stronger connections between communities, and intensified exchanges of knowledge and goods. In these maps, areas with full colour lines correspond to high inter-site similarity, while highly transparent areas indicate absolute diversity (i.e., minimal similarity).

conditions becoming more favourable after 7200 BCE, the population remained low until a gradual increase which started around 6500 BCE. This discrepancy raises questions about potential research biases that led to an over-representation of coastal sites to the expense of inland ones. It is possible that inland sites from this period are more frequent than currently expected, as suggested by discoveries in areas like Duqm (DUQ-25 in Al-Wusta Governorate, [Maiorano et al. 2024](#)), but research in these regions is still in its early stages, making it difficult to draw on them even for preliminary conclusions.

From 6000 BCE, proxies for human presence and activity begin to rise gradually, coinciding with the peak of the Holocene Humid period ([Figure 10](#)). This period saw an increase in the number of sites, a higher number of projectile points, and initially lower diversity ([Figure 10](#)). After a brief arid interval between 5400 and 5200 BCE, there was a peak in the number of points as well as in their diversity, followed by a consistent increase in population. However, the population reached its highest levels in the 5th millennium BCE, during wet conditions, which occurred slightly later than currently indicated by the artefact record.

In the final phase of the study period (after 4000 BCE), climatic proxies hint at the onset of drier conditions, while demographic proxies show potentially higher population density paired with a decline in the number of artefacts and an increase in artefact diversity. ([Figure 10](#)). This decline in the number of tools, which began ca. 4500 BCE, raises questions about a possible gradual shift in subsistence strategies, e.g. a decrease in hunting in favour of an increased reliance on fishing and possibly pastoralism, while the peak in diversity might also suggest higher localism and subregional differences.

4. DISCUSSION

Our analysis of Holocene population dynamics in Southern Arabia, which integrates archaeological and palaeoclimatic proxies, reveals substantial correlations between demographic trends and climatic variability in southern Oman, while more ephemeral trends emerged for northern Oman and the UAE. During the Early Holocene, population growth corresponds with wetter conditions, mirroring broader Near Eastern patterns in which increased precipitation drove demographic expansion ([Palmisano et al. 2021b](#)). Archaeological evidence supports this interpretation: projectile-point assemblages across Oman and the UAE display strong technological continuity ([Maiorano et al. 2020a](#)), suggesting cohesive population networks facilitated by increased mobility and favourable environmental conditions.

Across the Early and Middle Holocene, demographic expansion broadly coincides with periods of enhanced humidity. This pattern is clearer in the positive

correlations between demographic proxies and the Qunf $\delta^{18}\text{O}$ record, while correlations with the Hoti record remain weak and temporally inconsistent ([Figure S1–S2](#); [Figure 10](#)). Between ~8800 and 7400 BCE, demographic and hydro-climatic proxies rise together, marking a regional expression of the Holocene Humid Period. This agreement across independent demographic indicators such as SPD, composite KDE, and raw point counts, ([Figure 10](#)) supports the interpretation of a sustained population maximum under ameliorated climate.

Between ~7000 and 6000 BCE, the hydroclimatic trend continues to rise, yet our proxies indicate a synchronous decrease in population levels, a reduction in the number of points, and a marked increase in technological diversity. This pattern may reflect growing isolation among regional communities, although it remains unclear whether the apparent demographic contraction and the higher diversity are genuine evidence or rather the result of research and sampling bias leading to smaller sample sizes. This uncertainty highlights an important avenue for future fieldwork. Recent discoveries already point in this direction: the site of Wadi Sayy DUQ-25 A (Duqm, Al-Wusta, Oman), dated to the 7th millennium BCE, demonstrates that inland regions were inhabited during this period ([Maiorano et al. 2025b](#)). It is therefore likely that additional, yet undated, sites exist in the interior of Oman, and that the perceived demographic decline may partly stem from the current lack of chronological evidence rather than an actual reduction in population.

Technological change during the Middle Holocene further reinforces this picture. Decreasing variability, with the emergence of planoconvex and trihedral points (~6400–5700 BCE) followed by increased diversity in point styles and manufacture techniques (~5600–4900 BCE), suggest that communities developed local variants in tool-making practices while still relying on a) shared technological backgrounds, and b) long-distance exchange as supported by the presence of trihedral points in the wide regions ranging from Yemen to Marawah Island in the UAE ([Crassard et al. 2020, 2023](#); [Charentier 2004](#)).

Notably, the progressive aridification indicated in the Hoti and Qunf records (after ca. 5600 BCE) does not coincide with demographic fluctuations. Instead, population levels reach a plateau, and technological diversity appear to increase ([Figure 10](#)). This trend recorded in technological variability after 5600 BCE, together with stable or rising demographic indicators despite declining monsoon intensity, suggests that social and technological adaptations played an increasingly important buffering role. Although causality cannot be inferred from these exploratory analyses, resilience can be hypothesised from the persistence and differential adaptation of human activity under worsening environmental conditions.

Toward the second half of the Middle Holocene, population trends appear increasingly regionally variable. Some areas continued to flourish, while others experienced stagnation or decline, likely reflecting local hydrological conditions, differential access to freshwater, and divergent strategies of mobility and resource use. As shown in previous work ([Charpentier et al. 2023](#); [Maiorano et al. 2020a](#)), lithic assemblages also become more diverse and regionally specific during this period. The decline of once widespread projectile-point types, such as trihedral points, and the emergence of localized styles, including the Sharbithat points in Dhofar, illustrate a growing fragmentation of cultural traditions and possibly an increasing emphasis on coastal occupations, as suggested by the rise in sites dated to the late 5th and 4th millennia BCE. Taken together, the demographic and correlation patterns indicate a growing north-south climatic divergence: monsoon-driven humidity in southern Oman is strongly aligned with demographic trends, whereas northern Oman's winter rainfall regime does not show any sustained demographic signal. Together, these patterns indicate that although climate shaped broad demographic trajectories, local socio-economic adaptations, mobility, and technological choices may have supported differential regional outcomes.

By the Late Holocene, demographic trajectories in the eastern part of Southern Arabia diverged from those observed in other parts of Southwest Asia ([Palmisano et al. 2021b](#)). Whereas societies with institutionalised social organization elsewhere often exhibit prolonged declines or marked collapses during phases of aridification, the Southern Arabian record explored here points to more heterogeneous responses. In some regions technological innovation, intensified fishing, increased occupation of lagoonal and mangrove environments, flexible and mobile settlement systems, and expanded mobility networks helped mitigate environmental stress ([Palmisano et al. 2021b](#)). From around 3200 BCE onward, the development and sustained use of oasis environments, supported by groundwater resources and later by early irrigation practices, provided an additional adaptive strategy that enabled long-term settlement continuity in several areas of Oman and the UAE. Conversely, regions more dependent on localised ecological niches, particularly inland zones lacking such hydrological buffers, may have remained more exposed to water scarcity, prompting alternative adaptive pathways and producing more volatile demographic histories.

The present spatial and chronological scope, as well as the exploratory nature of the methods adopted, do not allow us to disentangle all causal mechanisms linking climate and population dynamics. Rather, this study offers the first systematic long-term comparison of demographic, technological, and palaeoclimatic proxies for Southern Arabia. Increased aridity generally corresponds

with demographic decline or cultural isolation, whereas increased humidity supports population growth and technological transmission. Where correlations weaken or fail, alternative explanations, including groundwater availability, shifts in subsistence strategies, rapid demographic fluctuations, selective mobility, or internal cultural dynamics, must be considered.

Overall, the combined evidence from techno-complex variation, SPDs, composite KDEs, and aoristic cluster trends supports a two-phase relationship between demography and environment in the eastern part of Southern Arabia:

1. an Early Holocene phase dominated by strong climatic control and shared technological solutions.
2. a Middle-to-Late Holocene phase marked by partial climatic decoupling, growing adaptive capacity, and increasing regional differentiation.

4.1 COMPARISON WITH PREVIOUS STUDIES

Compared to the synthesis by Palmisano et al. ([2021b](#)), which examined population and climate relationships across Southwestern Asia from 14,000 to 2500 cal BP, our study benefits from a denser radiocarbon dataset focused specifically on Southern Arabia, enabling a finer temporal resolution especially for the Early and Middle Holocene. Palmisano and colleagues showed that while early demographic trends were tightly coupled to climate, population dynamics later became increasingly autonomous as stratified societies emerged. Our results partly confirm this trajectory but highlight regional specificity: the Arabian record displays a shorter, more localized demographic decline and a rapid recovery rather than the prolonged "Dark Millenniums" observed elsewhere (cf. [Petraglia et al. 2020](#); [Uerpmann et al. 2009](#); [Figure 11](#)).

From ca. 6000 BCE, substantial population growth during the Middle Neolithic coincides with the most humid phase of the Holocene, followed by gradual decline during aridification after 3800 BCE. The increased number of securely dated sites between 5500 and 4500 BCE refines the timing of the demographic peak observed by Palmisano et al. ([2021b](#)) ([Figure 11](#)). The apparent contraction around 4500–4200 BCE may represent a brief episode of environmental stress and isolation rather than a collapse. Population levels rose again between 3900 and 3500 BCE but declined sharply toward the end of the Late Neolithic in association with more arid and unstable climatic conditions.

The widespread diffusion of advanced projectile technology, improved fishing practices, and flexible occupation strategies contributed to demographic growth during the Holocene Humid Period ([Magee 2014](#); [Charpentier et al. 2023](#)). Later, the onset of aridity appears to have stimulated technological and social innovation, setting the stage for Bronze and Iron

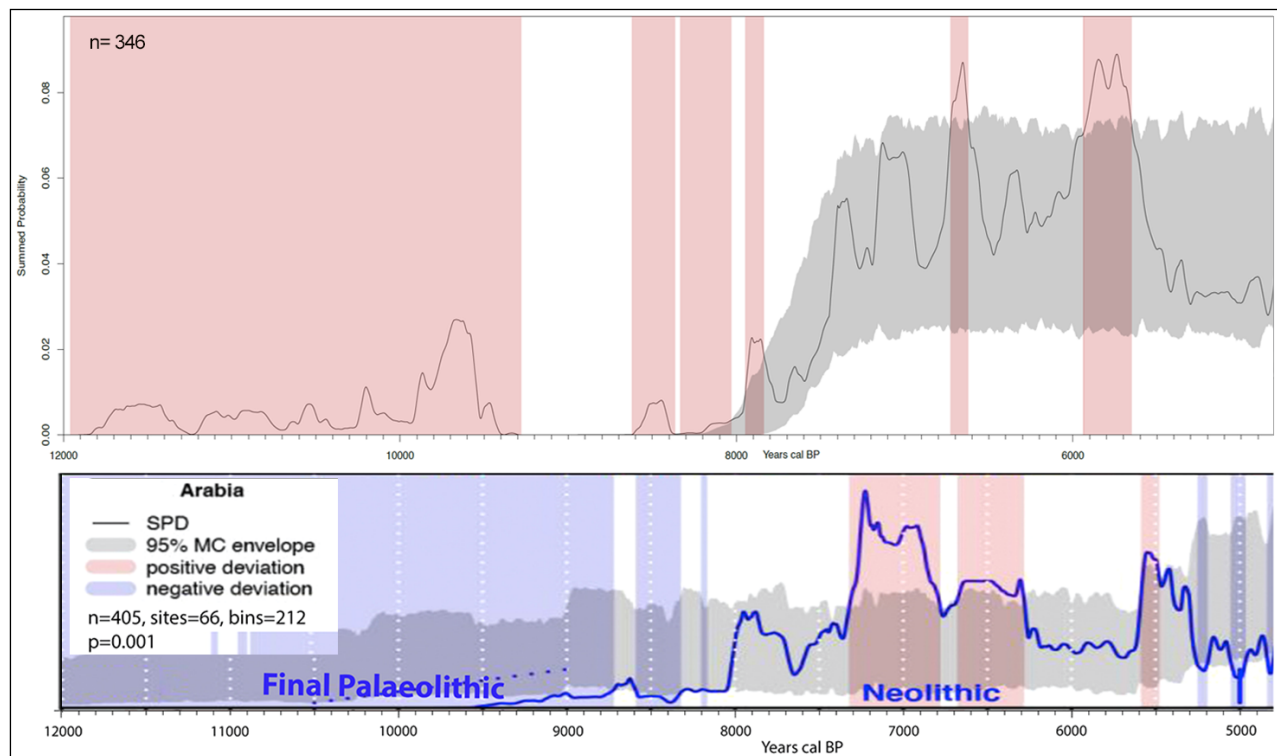


Figure 11 Summed Probability Distribution (SPD black line) of normalized calibrated radiocarbon dates compared with the SPD reported by Palmisano and colleagues (2021b).

Age transformations, including oasis exploitation and irrigation-based agriculture (Magee 2014; Schmidt et al. 2025, this volume). These patterns potentially support the diffused hypothesis that the development of subsistence strategies and technology among Holocene populations of Southern Arabia developed independently and building on local innovations rather than relying on external Neolithic migrations from the Levant (Cleuziou & Tosi 2007; Crassard 2008; Maiorano et al. 2020a; Charpentier et al. 2023).

Future research will need to integrate additional archaeological and demographic proxies across broader temporal and spatial scales. Higher-resolution palaeoclimatic archives, particularly pollen-based reconstructions, will be critical to refine the environmental backdrop of demographic change. Expanding the radiocarbon database—especially for inland Neolithic contexts—remains critical to reducing chronological uncertainty and overcoming research biases that still constrain our interpretations.

5. CONCLUSION

This study provides the first integrated assessment of demographic, cultural, and climatic trends in Southern Arabia from 10,000 to 3,000 BCE using a multi-proxy framework that combines radiocarbon-based demographic modelling, point-cluster analyses, and high-resolution speleothem records. Our results identify

several intervals in which demographic and climatic trajectories align—especially before 7500 BCE, around 4700 and 4400 BCE, and after 3400 BCE—supported by corrected SPDs, cKDEs, Hill’s diversity indices, and moving-window correlations. These periods show the strongest correspondence between demographic growth and wetter phases, particularly in relation to the Qunf record.

Beyond these intervals, patterns become more ambiguous. The weak correlations with the Hoti record and the clearer relationships with Qunf highlight a regional divergence between northern and southern Oman, reflecting differing hydroclimatic regimes. In addition, residual sampling biases, taphonomic gaps, and uneven research intensity likely contribute to some mismatches between climatic and demographic proxies, especially in the Late Holocene when SPDs and survey-based indicators diverge.

Nevertheless, the intervals of stronger coupling, shows the importance of climatic amelioration for population growth during parts of the Early and Middle Holocene. At the same time, archaeological evidence points to adaptation and resilience: communities diversified subsistence strategies, adjusted mobility and settlement patterns, and increasingly exploited wetlands, mangroves, and later oases to buffer aridification. The association between demographic proxies and technological diversity further suggests that cultural flexibility aided adaptation, even if innovation cannot be always quantified directly.

Methodologically, the integration of CA, MCA, aoristic modelling, and SPDs, together with comparisons to survey data and shell/charcoal SPDs, proved effective for detecting structure and assessing biases in the archaeological record. These findings demonstrate how combining climatic proxies with quantitative analyses of material culture and radiocarbon chronologies can guide archaeological interpretation, open new analytical pathways, and establish a clearer environmental framework for understanding long-term demographic processes. Still, research gaps persist, especially regarding inland, Early Holocene, and high-resolution palaeoenvironmental datasets.

Future work should expand survey coverage in desert and peri-desertic zones, refine palaeoclimatic chronologies, and incorporate vegetation-based reconstructions to better resolve climate–population–landscape interactions.

Overall, our results show that human–environment dynamics in Southern Arabia were entangled but neither uniform nor linear. Climatic change possibly influenced demographic patterns during key intervals, but cultural strategies and ecological flexibility were central to persistence and reorganization in increasingly arid landscapes. At the same time, this work should be seen as a foundational, exploratory step: rather than offering definitive answers, it aims to challenge existing datasets and long-standing interpretations, highlighting how much remains to be discovered, refined, and debated as new evidence and methods continue to emerge.

DATA ACCESSIBILITY STATEMENT

All used data and codes are included in the supplementary materials. Original data source for detailing attributes of projectile points is available upon request from the authors.

ADDITIONAL FILES

The additional files for this article can be found as follows:

- **Supplementary File 1.** S1 data – List of projectile points from Oman and UAE used in this study. DOI: <https://doi.org/10.5334/oq.151.s1>
- **Supplementary File 2.** S2 dates_om_uae_clean – Radiocarbon datings from Oman and UAE used in this study. DOI: <https://doi.org/10.5334/oq.151.s2>
- **Supplementary File 3.** S3 data_newclusters – Projectile points obtained techno-clusters. DOI: <https://doi.org/10.5334/oq.151.s3>
- **Supplementary File 4.** S4 Codes_Maiorano_Bortolini.R. DOI: <https://doi.org/10.5334/oq.151.s4>
- **Supplementary File 5.** S5 Hoti – Hooti Cave z-score. DOI: <https://doi.org/10.5334/oq.151.s5>
- **Supplementary File 6.** S6 Qunf – Qunf Cave z-score. DOI: <https://doi.org/10.5334/oq.151.s6>
- **Supplementary File 7.** S7 Palaeoenvironmental proxy from Hoti Cave. DOI: <https://doi.org/10.5334/oq.151.s7>
- **Supplementary File 8.** S8 Palaeoenvironmental proxy from Qunf Cave. DOI: <https://doi.org/10.5334/oq.151.s8>
- **Supplementary File 9.** S9 Moving-window Pearson correlations between corrected SPD and $\delta^{18}O$ records from Hoti cave (*movingWin_Hoti.csv*). DOI: <https://doi.org/10.5334/oq.151.s9>
- **Supplementary File 10.** S10 Moving-window Pearson correlations between corrected SPD and $\delta^{18}O$ records from Qunf cave (*movingWin_Qunf.csv*). DOI: <https://doi.org/10.5334/oq.151.s10>
- **Supplementary File 11.** S11 Hamming.dist.R. DOI: <https://doi.org/10.5334/oq.151.s11>
- **Supplementary File 12.** S12 Basic Terminology. DOI: <https://doi.org/10.5334/oq.151.s12>
- **Supplementary File 13.** S13 Supplementary materials - Reference list. DOI: <https://doi.org/10.5334/oq.151.s13>
- **Supplementary File 14.** S14 Sites_and_Chrono bins. DOI: <https://doi.org/10.5334/oq.151.s14>

FUNDING INFORMATION

The research was funded by the Academy of Sciences and by the Czech Ministry of Education, Youth and Sports, project reg.no. CZ.02.01.01/00/22_008/0004593.

COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

Maria Pia Maiorano: Conceptualization, Methodology, Investigation, Data curation, Writing, Review & editing, Visualization. Eugenio Bortolini: Conceptualization, Methodology, Formal analysis, Writing, Review & editing, Supervision.

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TO CITE THIS ARTICLE:

Maiorano, MP and Bortolini, E. 2026. Southern Arabia Population Patterns and Intensity of Cultural Exchanges Across the Holocene Humid Period. *Open Quaternary*, 12: 1, pp.1–22. DOI: <https://doi.org/10.5334/oq.151>

Submitted: 31 July 2024 **Accepted:** 01 January 2026 **Published:** 22 January 2026

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