Comparing summed probability distributions of shoreline and radiocarbon dates from the Mesolithic Skagerrak coast of Norway

Isak Roalkvam[1,*]   Steinar Solheim[2]

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[1] University of Oslo, Institute of Archaeology, Conservation and History
[2] University of Oslo, Museum of Cultural History

[*] Correspondence: Isak Roalkvam <isak.roalkvam@iakh.uio.no>

1   Introduction

Variation in population patterns are regarded as important drivers and potential consequences of cultural variation, and is thus of critical importance to our understanding of past human societies (e.g. French et al., 2021; Shennan, 2000; Shennan and Sear, 2021). During the last decade, the frequency distribution of radiocarbon dates have become the preferred proxy for archaeologists studying prehistoric population dynamics (Crema, 2022; French et al., 2021; Shennan et al., 2013), owing in part to the fact that radiocarbon dates represent the most temporally and spatially widespread archaeological data available for studying past population densities (Bird et al., 2022). This has also been the case for Norwegian Stone Age archaeology (Bergsvik et al., 2021; Jørgensen et al., 2020; Lundström et al., 2021; Nielsen, 2021a; Nielsen et al., 2019; Solheim, 2020; Solheim and Persson, 2018; see also Persson, 2009).

The potentially immense value of insights into population dynamics, combined with the ubiquity of radiocarbon dates and the relative ease with which these can now be processed within what has been termed a dates-as-data methodology (Rick, 1987) has undoubtedly contributed to the popularity of the approach. Several limitations and forms of criticism have, however, been directed at these procedures. Some of the objections are of a methodological nature, while others pertain to the underlying logic and the degree to which there is likely to be a direct connection between the frequency of ^{14}C-dates and population dynamics (e.g. Attenbrow and Hiscock, 2015; Carleton and Groucutt, 2021; Torfing, 2015; Ward and Larcombe, 2021). What appears to be agreed upon by practitioners and critics alike is that radiocarbon dates are best analysed in this manner when compared and contrasted to other proxies for past population dynamics, and other variables that might impact these (Attenbrow and Hiscock, 2015; Bevan et al., 2017; French et al., 2021; Palmisano et al., 2021, 2017; Williams, 2012). In this paper, we aim to report on and begin to unpack the relationship between two measures that have been linked to relative population size in the context of the Mesolithic Skagerrak coast in south-eastern Norway, namely the summed probability distribution of calibrated radiocarbon dates (RSPD) and the summed probability distribution of shoreline dated sites (SSPD). We discuss how the data compare with each other as well as how it can potentially be used to understand cultural historical development in the region through the Mesolithic, c. 9500–4000 BCE.

2   Background

Following the retreat of the Fennoscandian Ice Sheet, large parts of the post-glacial landscape of Northern Scandinavia has been characterised by dramatic isostatic uplift that has led to a net sea-level fall throughout

the Holocene, despite eustatic sea-level rise (e.g. Mörner, 1979; Steffen and Wu, 2011). The majority of Mesolithic sites along the Norwegian Skagerak coast are interpreted as having been shore bound or at least located close to the contemporaneous shoreline at their time of use. As coastal foragers in this region appear to have predominantly settled on or close to the contemporaneous shoreline during early and mid-Holocene, this can be utilised to assign an approximate date to the sites. This is done by coupling the present-day altitude of the sites with reconstructions of past shoreline displacement – a method known as shoreline dating. Shoreline dating has a long tradition of use in Norwegian archaeology (Brøgger, 1905), and is especially useful for dating the large number of surveyed archaeological sites where temporal data that often follow with an excavation, such as radiocarbon dates or typological indicators in artefact inventories, are not available. Previous studies have suggested that shoreline dated sites can be used as a proxy to study temporal variation in population and settlement patterns (Jørgensen et al., 2020; Mjærum, 2022; Solheim and Persson, 2018; Tallavaara and Pesonen, 2020).

Previously, the frequency of shoreline dated sites has been compared to RSPDs by finding point estimates of shoreline dates that are aggregated in somewhat arbitrary bins of 200 or 500 years, or by the use of disjoint time-intervals of variable duration (Berg-Hansen et al., 2022), which could cause issues when comparing the relative counts across these units (Bevan and Crema, 2021). The point-based estimates do therefore not consider the uncertainty in the distance between the sites and the contemporaneous shoreline, nor the impact the variability in the rate of sea-level change has on the precision of the dates that can be achieved with the method. In a recent study, Roalkvam (2023a) has presented a probabilistic method for shoreline dating that takes these parameters into account, thus setting the stage for a more refined investigation of the relationship between the frequency of ^{14}C-dates and shoreline dated sites. The parametrisation of the method was based on simulating the distance between 66 sites with ^{14}C-dates and the prehistoric shoreline along the Skagerrak coast in the region between Horten municipality in the northeast to Arendal municipality in the southwest (see map in Figure 1). The results of the analysis indicates that the sites tend to have been located close to the shoreline until just after 4000 BCE when a few sites become more withdrawn from the shoreline (see also Nielsen, 2021b), followed by a clear break around 2500 BCE, at which point shoreline dating appears to lose its utility. Thus, this geographical and temporal limit are also used for this study.

The present study is decidedly exploratory. While some thoughts concerning the relationship between the variables outlined above underlie the analysis, these could not be instantiated as concrete hypotheses. Rather, we explore the data by using a set of standard models to begin to unpack patterns and grasp the relationship between the variables. The dates-as-data approach is dependent on there being a link between how prehistoric people generated material that become ^{14}C samples and population dynamics (cf. Freeman et al., 2018). The sum of shoreline dated sites, on the other hand, is determined by site frequency, and its use as a population proxy is therefore dependent on there being a connection between site count and population density. If a comparison of these proxies do not, or only partially correspond, it is thus an open question what factors have impacted either distribution to cause this discrepancy, and which measure, if any, reflects true population dynamics. The issue will therefore initially demand an open and exploratory approach where a multitude of explanatory and confounding effects can be drawn on to suggest explanations of any observed pattern.

2.1 Population dynamics and summed probabilities

To what degree the radiocarbon record is determined by past population numbers might vary geographically and chronologically, based on variation in investigatory and taphonomic factors (Bluhm and Surovell, 2019; Surovell et al., 2009), as well as cultural processes within prehistoric populations. One example of the latter is the difference that might exist between farmer and forager populations, where Freeman et al. (2018) have suggested that an increased per capita energy consumption introduced with farming means that ^{14}C-dates should not be weighted equally when making relative population estimates across such populations. Similarly, while site counts have also been invoked for the analysis of past population dynamics, these are likely to be impacted by factors such as land-use and mobility patterns, and settlement nucleation and dispersion, as well as variation in archaeological investigations and what has been taken to constitute a 'site' (Palmisano et al., 2017). However, these could be considered theoretical issues that have implications for how fluctuations in these proxies should be interpreted, and possibly weighted differently according some criteria. Before any

such fluctuations are given any substantive interpretation, however, there is a host of methodological issues that have to be considered (see Carleton and Groucutt, 2021; Crema, 2022 for reviews).

The most critical of these follow from the fact that the summation of the probabilities associated with the dates for SPDs is not a statistically coherent procedure. This is because the summed probabilities can no longer been seen as probabilities, but rather represent the combination of events and chronological uncertainties, making the two indistinguishable, and rendering the interpretation of the resulting sum difficult (Blackwell and Buck, 2003; Crema, 2022). As Timpson et al. (2021, p. 2) put it: 'the SPD is not *the* single best explanation of the data, nor even *a* single explanation of the data, but rather a conflation of many possible explanations simultaneously, each of which is mired by the artefacts inherited from the calibration wiggles.' The SPD is not a model. It is the combined representation of a range of possible explanations for the data – the frequency of dated events combined with the variable uncertainty associated with these (Carleton and Groucutt, 2021). This means that a direct visual inspection of SPDs can be misleading, that they cannot be directly analysed to draw inferences on population dynamics, and that they cannot be directly compared to other time-series data (Carleton et al., 2018; Crema, 2022; Timpson et al., 2021). While this problem can never be entirely resolved, a range of approaches have been developed in an attempt to work around this issue.

The most commonly applied of these is a null-hypothesis significance testing approach by means of Monte Carlo simulation, first introduced by Shennan et al. (2013) and later expanded upon by Timpson et al. (2014) and Crema and Bevan (2021). This works by comparing the observed RSPD with a series of simulated RSPDs, generated from a null model. These null models are typically a uniform, exponential or logistic distribution. These are chosen *a priori* with reference to common long-term population dynamics and are typically parametrised by fitting the models by means of least-squares or maximum likelihood estimation (MLE). The result from these simulations are then used to create a 95% critical envelope representing the null model. The proportion of the observed RSPD that falls outside the simulated envelope (i.e. positive or negative divergence of the observed SPD from the fitted null model), is then used to estimate a global p-value indicating whether the null model can be rejected. In the case that it can, the portions of the observed RSPD that falls outside this envelope can subsequently be interpreted as representing potentially meaningful demographic events, relative to the null model. However, care has to be taken in how these are interpreted. First, this follows from the fact that 5% of the deviations from the critical envelope can be expected to be random, and there is no way to know which deviations this pertains to. Secondly, a for example exponential null model fit to the data is only one of an infinite set of exponential models with different growth rates that could be used. While a model fit by means of MLE will likely have a reasonable growth rate, and by extension exclude many other exponential fits as likely to explain the data, this can be difficult to determine. Finally, the p-value only indicates whether or not the null model as a whole can be rejected as an explanation of the data, and does not provide statistical justification for inferring whether local deviations themselves are meaningful demographic signals (see review by Crema, 2022; Timpson et al., 2021).

The procedure outlined above represent the standard approach in efforts to model population dynamics based on RSPDs. This can be helpful for getting an impression of the overall developments of population proxies, and is an especially useful first step in the treatment of shoreline dated sites done here, as few assumptions concerning this overall development could be made. However, standard models frequently used to evaluate RSPDs are consistently being rejected in the literature and it is worth underscoring, as mentioned above, that deviations from these rejected null models do not in themselves allow for any interpretations of the local deviations, nor a subsequent direct analysis of the SPDs themselves.

3 Methods and data

Sites surveyed by means of test-pitting between Horten and Arendal were initially retrieved from the national heritage database Askeladden (Norwegian Directorate for Cultural Heritage, 2018), totalling at 1299 records. The records were then manually reviewed and given a quality score based on the criteria in Table 1, indicating the degree to which the spatial location and extent of the sites is believed to be represented in the geometries available in the database (see also Roalkvam, 2020). All sites with a quality score of 4 or worse were excluded

Table 1: Quality scoring of site records of surveyed sites retrieved from the national heritage database Askeladden. The scoring system was first used in Roalkvam (2020).

Definition	Quality	Count
Site delineated by use of a GNSS-device, or a securely georeferenced record. Extensive database entry.	1	353
Secure spatial data. Slight disturbance of the site or somewhat lacking database record.	2	340
Secure spatial data. Damaged site, such as outskirts of a quarry, and/or very limited database entry.	3	148
Surveyed by archaeologists. However, the database entry is extremely limited/unclear, the site geometry is only given as a point or small automatically generated circle, and/or finds are from the topsoil of a field.	4	165
Likely site but uncertain spatial information. Typical example is recurring stray finds in a field or other larger area.	5	124
Single stray find or unverified claims/suggestions of possible site.	6	169

from further analysis. Any sites situated at elevations that result in a shoreline date earlier than 9465 BCE were then excluded. This marks the latest start-date among the employed displacement curves, and no sites have yet been verified to be older than around 9300 BCE in the region (Glørstad, 2016). Data on excavated sites was originally compiled for Roalkvam (2023a) and has been compared with site data as listed in Damlien et al. (2021) and Nielsen et al. (2019). Only excavated sites with available spatial data in Askeladden or local databases at the Museum of Cultural History of the University of Oslo were included in the analysis. The 102 excavated sites in the dataset without relevant ^{14}C-dates that were originally shoreline dated in the excavation reports were included in the SSPD along with the retained surveyed sites. This gave a total of 921 shoreline dated sites in the final SSPD.

The borders of the municipalities within which the shoreline dated sites are located were used to limit the radiocarbon sample. Radiocarbon dates were taken from Roalkvam (2023a) and (**solheim?**). Dates done on food crusts were then excluded due the issue of marine reservoir effects (Nielsen et al., 2019, p. 83). Following both from the point made by Freeman et al. (2018) concerning the comparison of radiocarbon dates from populations with different economic modes, as noted above, and from the fact that shoreline dating appears less reliable after 4000 BCE and appears to loose its utility c. 2500 BCE, the Mesolithic is the main focus of this analysis. Consequently, probabilities falling later than 2500 BCE were excluded from the analysis, leading to the final sample of 310 ^{14}C-dates. Probabilities falling after 4000 BCE and the first possible small-scale introduction of agriculture in south-eastern Norway were retained to account for edge-effects, but these results should be treated with care for the reasons noted above.

All analyses done in this study were performed using the R programming language (R Core Team, 2020). Underlying data and programming code used for the paper is available in a version-controlled online repository at X. This is structured as a research compendium following Marwick et al. (2018), to allow for reproducibility of the results (see also Marwick, 2017). Analysis of the ^{14}C-dates were done using the R packages *ADMUR* (Timpson et al., 2021) and *rcarbon* (Crema and Bevan, 2021). The R package *shoredate* was used for performing and handling the shoreline dating of sites (Roalkvam, 2023b), with re-purposed code from both *ADMUR* and *rcarbon* for Monte Carlo simulation and model comparison.

3.1 Summed probability of calibrated radiocarbon dates

To account for investigatory bias that can result from variable sampling intensity between sites, the summing of radiocarbon dates with *ADMUR* starts with binning dates from the same sites that fall within 200 uncalibrated ^{14}C years of each other when measured from the mean ^{14}C age. All dates are then calibrated using a resolution of 5 years and normalised to sum to unity. The RSPDs for each site-phase are summed to achieve the final SPD, which is in turn normalised. All calibrations were performed using the IntCal20 calibration curve (Reimer et al., 2020).

The final RSPD was subjected to the standard null-hypothesis testing approach through Monte Carlo simulation, as introduced above (see Shennan et al., 2013; Timpson et al., 2014), by fitting an exponential, logistic and uniform model to the observed RSPD. Following Timpson et al. (2021), the model parameters were identified by MLE search, using the differential evolution optimization algorithm *DEoptimR* (Brest
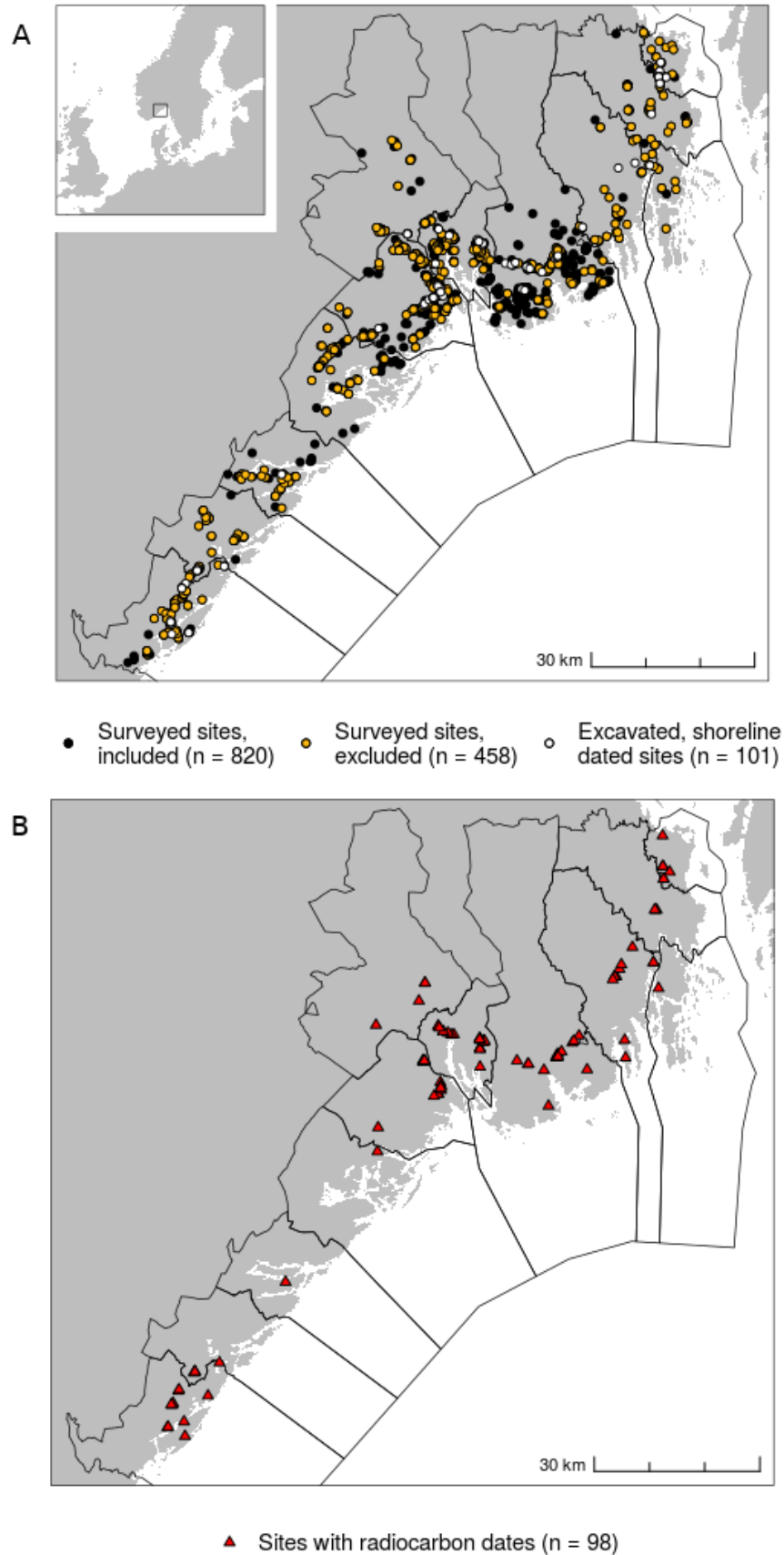
Figure 1: A) Map displaying the location of the study area and shoreline dated sites. Black lines indicate the borders between municipalities. The surveyed sites included in the analysis are the ones given a quality score of 3 or higher using the framework in Table 1. B) The distribution of radiocarbon dates employed in the study.

et al., 2006). The Monte Carlo simulations were then performed using the *SPDsimulationTest()* function from *ADMUR*. For each model, a series of individual calendar years are drawn from the model distribution, with replacement, the number of which equals the number of bins in the observed RSPD. These are then 'uncalibrated' to a single value on the ^{14}C scale and a random error from among the observed errors is added to the date. These are then calibrated back to the calendar scale and finally summed. Here, this procedure was repeated 10000 times for each null model. The 2.5th and 97.5th quantile of the resulting summed probability for each year across all simulations are then retrieved to create the 95% critical envelope with which to compare the observed RSPD. The degree to which the observed RSPD deviates from the critical envelope is used to calculate a global p-value, indicating whether the null model can be rejected.

3.2   Summed probability of shoreline dated sites

Summing the probability of the shoreline dated sites and the model-fitting procedures followed the same structure as that for radiocarbon dates and was partly based on re-purposed programming code from *rcarbon* and *ADMUR*. However, idiosyncrasies in the dating method did necessitate some adjustments. To illustrate this, the procedure for shoreline dating a single site, as suggested in Roalkvam (2023a), is provided in Figure 2 and outlined below.

Four geological reconstructions of shoreline displacement in the region lays the foundation for the method as implemented here (Figure 2B). These shoreline displacement curves are from Horten (Romundset, 2021), Porsgrunn (Sørensen et al., in press, 2014a, 2014b), Tvedestrand (Romundset et al., 2018; Romundset, 2018) and Arendal (Romundset, 2018), each associated with a shoreline isobase along which the trajectory for relative sea-level change has been the same (see Svendsen and Mangerud, 1987). The first step in the dating procedure is to interpolate the shoreline displacement to the site to be dated. This is done by inverse distance weighting (e.g. Conolly, 2020), where the relative sea-level change is interpolated to the location of an archaeological site based on its distance from the isobases of the geological displacement curves.

With an estimated trajectory of shoreline displacement at the site to be dated, the elevation of the site can be drawn on to find a likely date for when it was in use, under the assumption that it was in use when located on or close to the shoreline. Figure 2C indicates where the mean elevation of the polygon representing the example site intersects the interpolated displacement curve. As it can reasonably be assumed that a site was not in use when located under water, this effectively represents a *terminus post quem* (TPQ) date. A common approach to shoreline dating has been to find where the elevation of the site intersects the mean of the upper and lower limit of the displacement curve, and then adding a somewhat arbitrary error of $\pm$ 100 years to this point-estimate. However, TPQ dates that do not account for the likely distance between site and sea when the site was in use limits the further inferential steps that can be taken. Furthermore, the more common practice of adding a constant error to a point-estimate does not take into account that the rate of shoreline displacement varies both spatially and temporally, and therefore introduces bias to the result on both the spatial and temporal scale, while also overestimating the precision of the method in most cases.

This last point can be illustrated by finding the range between the upper and the lower limit of the four geological displacement curves for every meter from the marine limit and down to elevations that do not give an earliest date younger than 2500 BCE. This gives a mean TPQ range of 276 years with a standard deviation of 156 years across all four displacement curves, with this range varying significantly over time and between curves.

The analysis in Roalkvam (2023a) found that site phases ^{14}C-dated to before 2500 BCE have a likely elevation above sea-level that can be reasonably approximated by a gamma distribution with shape = 0.286 and scale = 20.833. This is incorporated in the procedure for shoreline dating used for this study (Figure 2D). When performing this dating procedure, the gamma distribution is sequentially stepped through and transferred to the calendar scale by uniformly distributing the probability across the years in the range between the lower and upper limit of the interpolated displacement curve. This procedure thus gives the shoreline date of a site when accounting for the likely elevation of the site above sea-level when it was in use (see Roalkvam, 2023a for details). Given that the shoreline displacement curves have no inversions and should therefore before commutative (cf. Weninger et al., 2015, p. 545), each shoreline date is normalised to sum to unity. To reduce

^{222} the computational cost of the simulation procedures to follow below, the gamma distribution is here stepped
^{223} through at increments of 0.1 m and the calendar scale is kept at a resolution of 5 years.
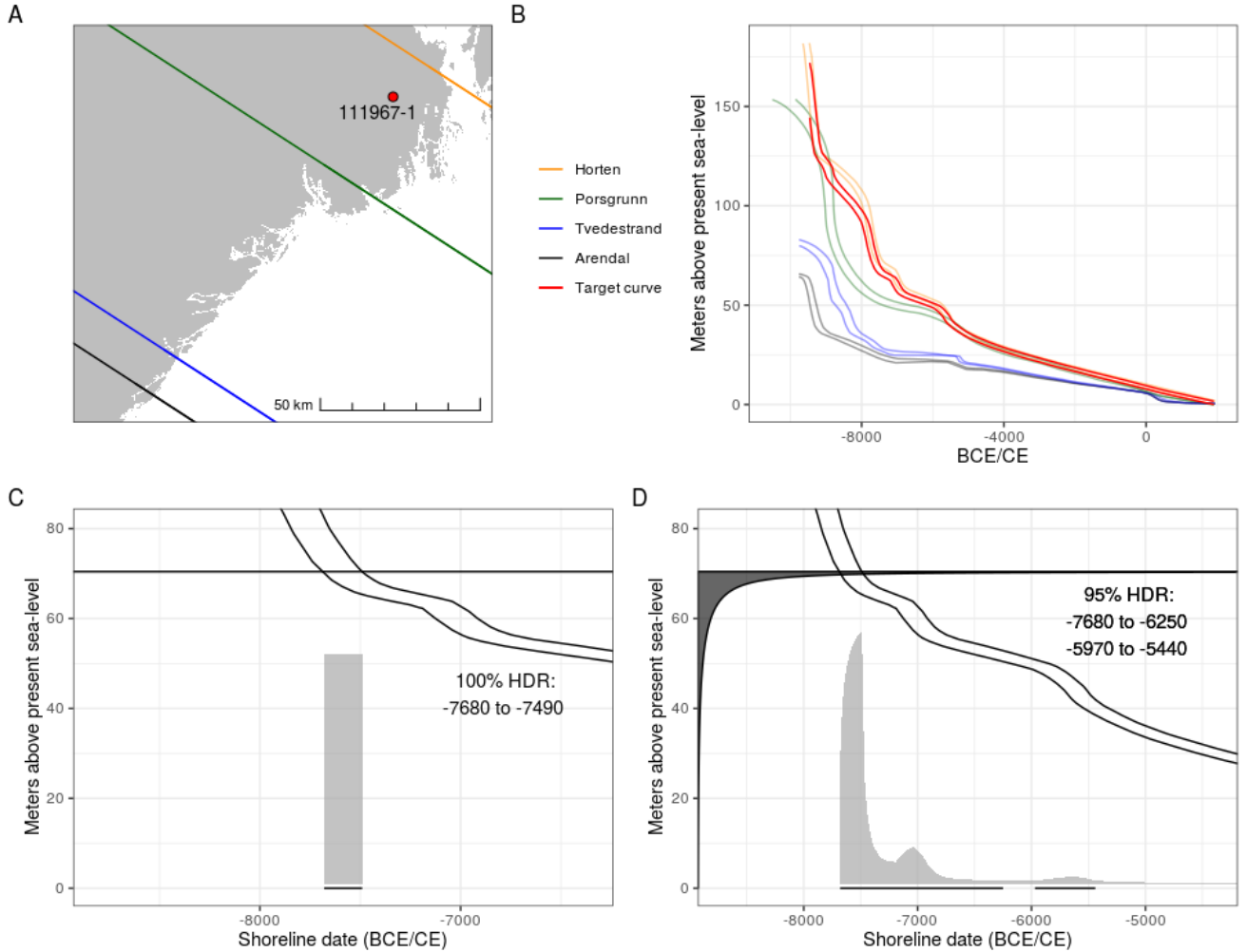

Figure 2: A) An example site (Askeladden ID 111967-1) relative to the isobases of the displacement curves. B) The geologically derived shoreline displacement curves for the region and the curve interpolated to the example site. C) The black line on the y-axis represents the elevation of the site. This crosses the interpolated displacement curve at 7680 and 7490 BCE, which thus in practice gives an estimate of when the location of the site emerged from the sea, giving a *terminus post quem* date. D) The shoreline dating approach used for this study, where the gamma distrbiution on the y-axis describes the likely vertical relationship between the shoreline and the site when it was in use.

^{224} The implications of different approaches to shoreline dating and summing the results are illustrated in Figure
^{225} 3. In Figure 3A the sites to be shoreline dated are plotted according to their elevation. Due to the variable
^{226} rates of shoreline displacement within the study region, the same elevation does not necessarily equate to the
^{227} same date, and so this does not directly inform us about their temporal distribution. For example, as the
^{228} trajectory for sea-level regression is more pronounced towards the north-east, the same elevation at a location
^{229} to the south-west implies a younger date compared to one situated further north-east.

^{230} When the frequency distribution of shoreline dates have been investigated in the past, this has typically
^{231} involved finding point-estimates of dates by either using the mean of displacement curves, or by taking mean
^{232} of the TPQ dates for each site (as illustrated in Figure 2C). These point-estimates are then aggregated

in bins of 200 or 500 years (e.g. Breivik, 2014; Fossum, 2020; Mjærum, 2022; Solheim and Persson, 2018; Tallavaara and Pesonen, 2020). This approach is illustrated in Figure 3B. The SSPD resulting from using the probabilistic method of shoreline dating, given in Figure 3C, demonstrates that accounting for the site-sea relationship gives a substantially different result compared to the more traditional approach, which is clearly indicated by the shifts in the positions of peaks and troughs in the distribution after c. 8000 BCE.
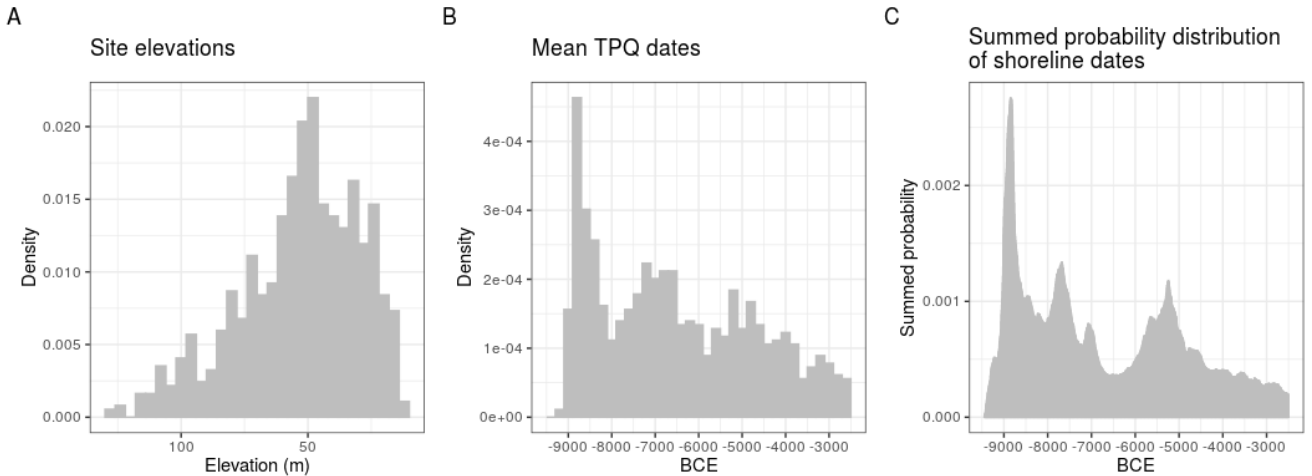

Figure 3: A) The distribution of the shoreline dated sites (n = 921) by altitude above present sea-level. The binwidth is 4 m. B) The mean of *terminus post quem* dates for the sites, plotted with a binsize of 200 years, reflecting the common approach to summing shoreline dates. C) The result of instead summing the probability of the shoreline dates achieved with the method employed here, which accounts for the likely distance between sites and shoreline. The binwidth is 5 years, following the resolution used with the dating procedure.

In the same way is with an RSPD, the SSPD cannot be directly interpreted as reflecting the intensity of sites over time, due to the summation issues introduced above. Furthermore, similar to how characteristics of the calibration curve can introduce bias to the RSPD, the same is true for the SSPD, where the local trajectory of relative sea-level change effectively functions as the calibration curve for each site. As the shoreline displacement curves are interpolated to the sites based on their location along a south-west/north-east gradient, each site is effectively associated with a unique shoreline displacement curve, provided they are not located on exactly the same isobase. With analogy to the radiocarbon methodology, this would be equivalent to each radiocarbon date being associated with a unique calibration curve. As it would be computationally prohibitive to interpolate the shoreline displacement trajectory for each date to be simulated in the Monte Carlo procedure, one shoreline displacement curve was initially interpolated to the centre of each of a series of 2 km wide line segments running perpendicular to the shoreline gradient between the extremes of the distribution of sites. These intervals were assigned a weight based on how the density of observed sites is distributed among them (Figure 4).

The Monte Carlo simulations with the SSPD is based on drawing a sample of calendar dates from the observed date range in the SSPD, equalling the number of shoreline dated sites, where the probability of drawing any 5 year interval is determined by the null model of choice. This is equivalent to the sampling method *calsample* from *rcarbon* (Crema and Bevan, 2021). Each sampled date is then assigned one of the pre-interpolated displacement curves, the probability of which is weighted by the density of observed sites within each 2 km interval. The calendar date is 'uncalibrated' – to follow the RSPD terminology – to an elevation range from which a single elevation value is drawn with uniform probability between the lower and upper limit of the displacement curve at that calendar year, using intervals of 5 cm. As shoreline dating is here done with a gamma distribution with the same parameters across all sites, there is no equivalent of the error term for ^{14}C-dates that determine the shape of the Gaussian distribution associated with the ^{14}C age. Consequently, the elevation value retrieved by 'uncalibrating' the shoreline date was shoreline dated using the displacement
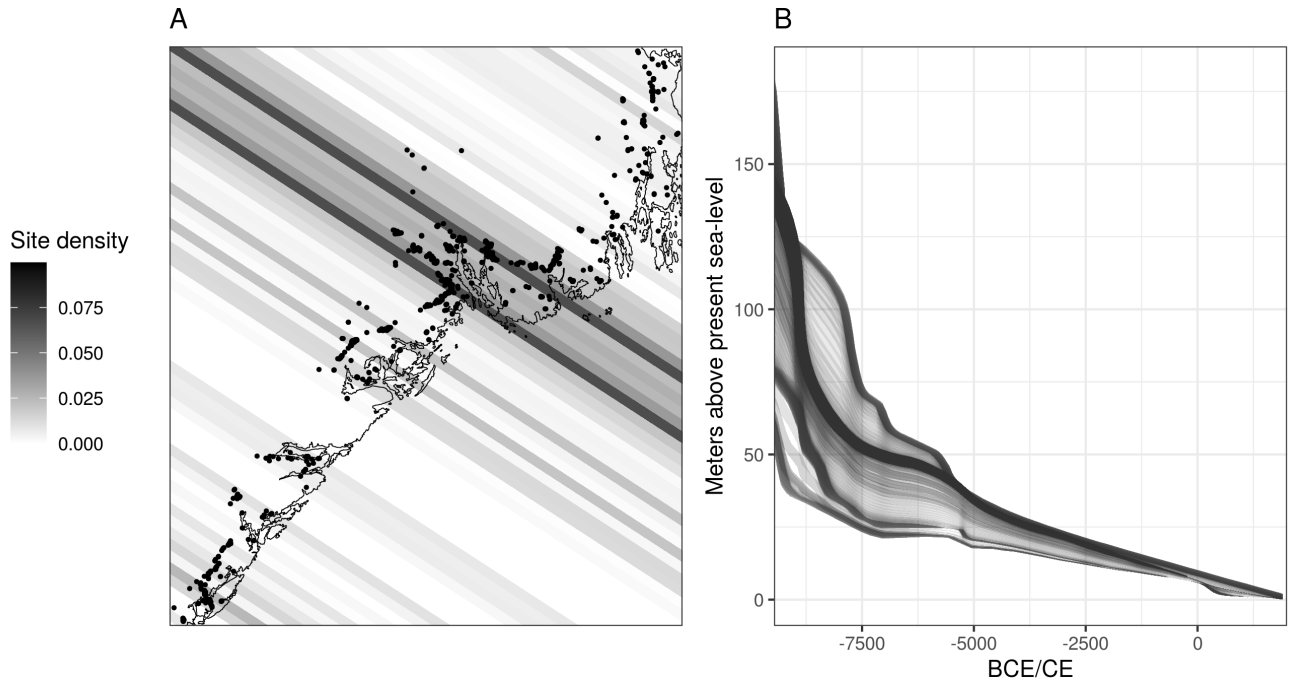
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Figure 4: A) Density of included surveyed sites and excavated sites dated by means of shoreline dating (n = 921) as distributed across 2 km wide line segments that run perpendicular to the shoreline gradient. B) The displacement curves interpolated to the centre of each segment for use in the Monte Carlo simulations below.

curve for the relevant 2 km interval with the same gamma distribution for all samples. Having dated the number of samples equalling the number of shoreline dated sites, these were then summed, and the entire process repeated a total of 10000 times. The 97.5% highest and 2.5% lowest summed probability at each interval of 5 years across all simulations was then retrieved to create the 95% critical envelope, and the global p-value found in the same manner as for the RSPDs. This was done using re-purposed code from *ADMUR*.

3.3 Comparing model performance

For each dating method, the relative performance of the exponential, logistic and uniform models was compared. This was done by finding the overall relative log-likelihoods of the models using the *loglik* function from *ADMUR*. For any given model, this involves finding the scalar product between the probability of each shoreline date against the probability of the null model, and in the case of the ^{14}C-dates, each site-phase. The overall model likelihood is the product of these individual probabilities and is not, critically Timpson et al. (2021), found by using the values of the final SPD. From these likelihoods, the Bayesian (or Schwarz) information criterion (BIC) was then found for each model. This penalises the models for the number of parameters in use, to avoid over-fitting, and can be used to compare the relative performance of the models.
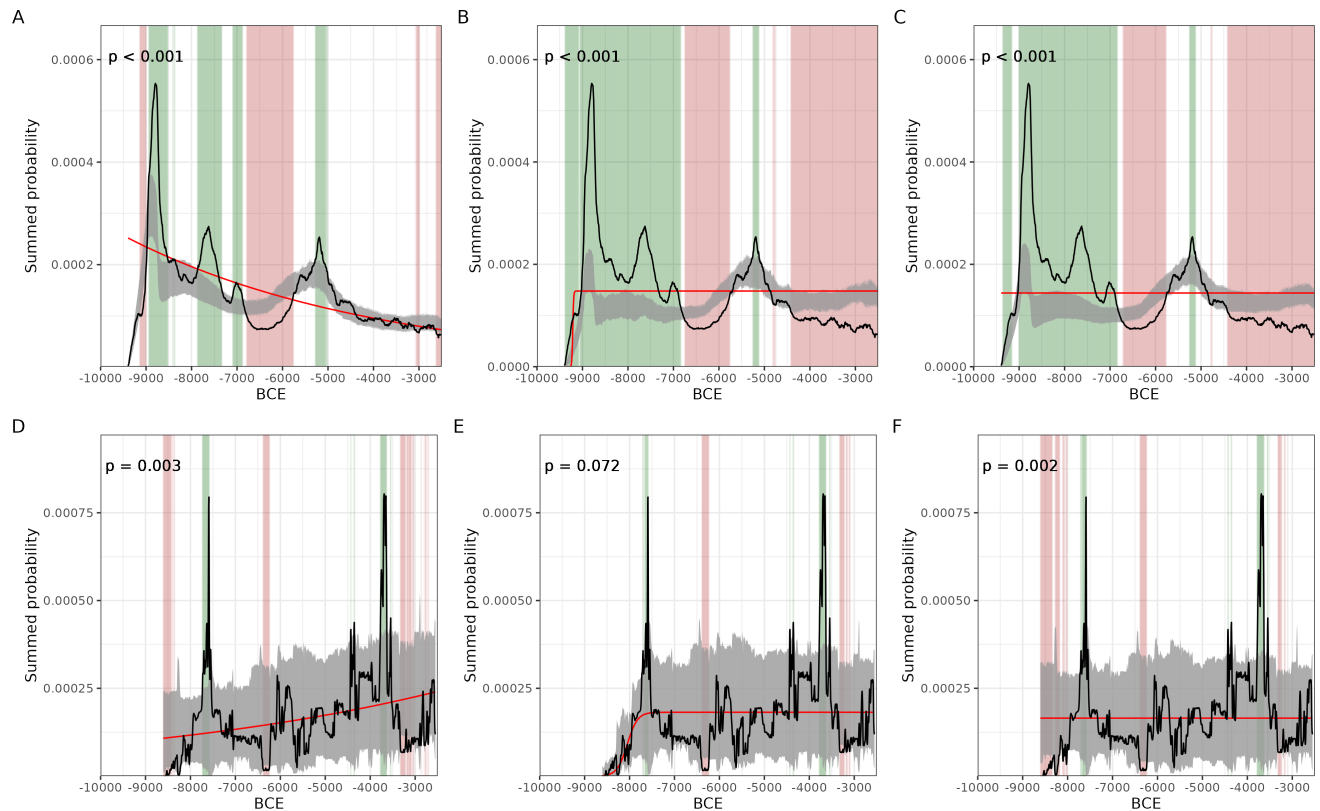
4   Results

Figure 5: Monte Carlo simulation for shoreline and radiocarbon dates. A) Summed probability of shoreline dated sites (n = 921) compared to an exponential null model. B) SSPD compared to a logistic null model. C) SSPD compared to a uniform null model. D) Summed probability of calibrated radiocarbon dates (n = 310, bins = 134) compared to an exponential null model. E) RSPD compared to a logistic null model. F) RSPD compared to a uniform null model.

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The results of the Monte Carlo simulations are given in Figure 5, displaying the deviations from the simulation envelopes and the corresponding global p-values. The comparison of the models based on BIC scores is given in Figure 6.

For the RSPD, the logistic model achieved a p-value of 0.072, and could therefore not be rejected (Figure 5E). As is also indicated by the BIC values, this model represents the best explanation of the data of the compared models, while the failure to reject the model means that the data could be expected under this logistic development. This is characterised by a rapid growth from the start of the RSPD, around 8500 BCE, which plateaus at around 7500 BCE and then remains stable for the remainder of the period.

All of the standard models could be rejected for the SSPD. Of the contrasted models, the BIC values indicate that the exponential model is the best candidate. Its negative direction indicates that some overall process of reduction in the frequency of shoreline dated sites occurs over time, while the rejection of the model and clear deviations from the exponential pattern indicates that this model does not account for the entire development (Figure 5A). Some significant deviations occurs with the model over-predicting the frequency of sites in the period from c. 9200–9000 BCE, followed by a significant positive peak just after 9000 BCE until around 8500 BCE. The process of decline is then interrupted by positive deviations at 7900–7400, and with a smaller deviation around 7000 BCE. This is closely followed by a negative deviation between c. 6800 and 5800 BCE. Finally, a positive deviation occurs again around 5300–5000 BCE. While all of the above deviations should also be viewed with caution, questions concerning the reliability of shoreline dating after 4000 BCE (cf. Roalkvam, 2023a) and the small magnitude of the negative deviations that occur around 3000 BCE means that these are disregarded in the discussion to follow.
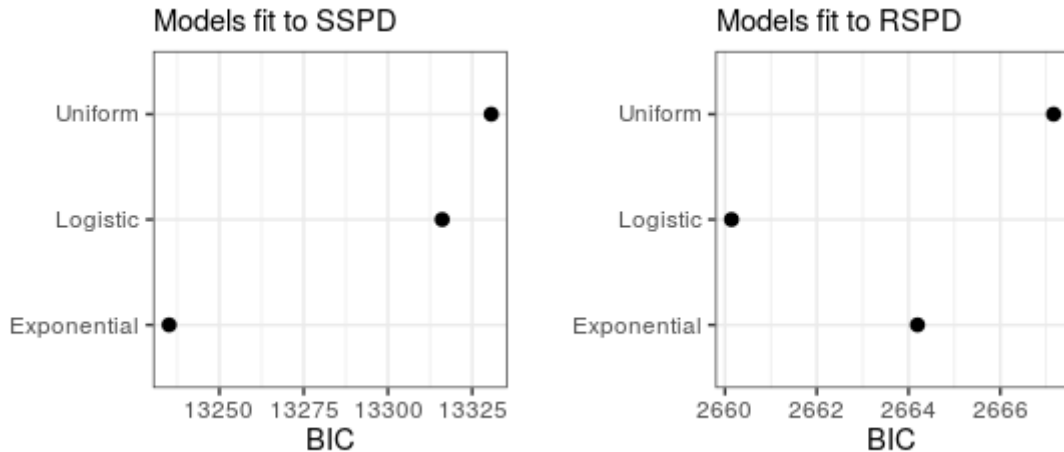

Figure 6: Bayesian information criterion for the models fit to the SPDs. Lower values indicate a better model.

5   Discussion

Although there are generally few ^{14}C-dates from the earliest part of the Mesolithic in Norway (e.g. Åstveit, 2018; Breivik and Bjerck, 2018; Kleppe, 2018; Solheim and Persson, 2018), it is established that Stone Age sites in southern Norway date to the period from before the earliest ^{14}C-dates in the study area for this paper, and at least from as far back as around 9300 BCE (e.g. Damlien and Solheim, 2018; Glørstad, 2016). While the SSPD achieved here starts from c. 9500 BCE, the RSPD shows no evidence of human activity until c. 8500 BCE. What has caused the lack of ^{14}C-dates from this earliest period has been given many possible explanations through the years. These range from taphonomic loss to diverse environmental and/or cultural factors, such as the use of shrubs or rapidly deteriorating seal blubber as fuel for burning, or a preference for consuming raw, dried or fermented food (see Bjerck, 2017; Damm, 2022). A possible lack of reliable access to

firewood has also been seen as possible contributor to this pattern, although evidence for the early presence of forested landscape, at least in the southern parts of the country, has now rendered this a less favoured hypothesis (Solheim and Persson, 2018; cf. Damm, 2022; Sørensen et al., 2014a). While taphonomic and ecological factors are likely part of the picture, we view it as probable that the rapid growth at the start of RSPD and the magnitude of the SSPD in the period preceding this suggest that cultural and demographic factors are central drivers behind this pattern.

The considered models also indicate that after the initial jumps of each proxy, some process of decrease in shoreline dated site frequency occurs throughout the period, contrasted by a general stationary frequency of ^{14}C-dated material. Following from what is generally held to be a reduction in residential mobility from the earliest to the later parts of the Mesolithic (e.g. Bang-Andersen and Bjerck, 2005; Bjerck, 2008, pp. 103–105; Fuglestvedt, 2018, pp. 16–17; Lindblom, 1984), an immediate explanation of this mismatch could be that the SSPD is more heavily impacted by variation in land-use and mobility patterns, while the RSPD mainly reflects population numbers.

A common interpretation of the Early Mesolithic in Norway is that the population was small but highly mobile, reflected in large numbers of short-lived sites along the coast (e.g. Bjerck, 2017, 2008; Fuglestvedt, 2012). This is commonly seen in relation to homogeneous lithic technology over large swathes of the Scandinavian Peninsula in this period, and what is believed to have been a rapid colonisation of the Norwegian coastline (e.g. Bang-Andersen, 2012; Bjerck, 2009; Fuglestvedt, 2012). High mobility has been seen as necessary both to maintain demographic viability among colonising groups, and for it to be possible to maintain this technological uniformity over large areas (Rowley-Conwy and Piper, 2017; also discussed by Berg-Hansen, 2018). The initial peak in the SSPD could thus be congruent with a process of rapid colonisation of the Norwegian coast, coupled with a high degree of mobility, leading to the overall high site-count in the earliest period. The lacking signal in the RSPD for the first settlement period could in this view reflect mobility patterns characterised by short occupational duration and corresponding pyrotechnology based on small, short-lived fires (cf. Damm, 2022) and low population numbers.

Following this earliest phase of rapid increase in shoreline dated sites, there is a drop from this initial peak, starting from around 8800 BCE, concluding around 8500 BCE and remaining within the simulation envelope until c. 7900 BCE. It has previously been suggested that a change in mobility patterns occurs some time around 8500–8300 BCE, involving a reduction in residential mobility (e.g. Damlien and Solheim, 2018; Roalkvam, 2022). Furthermore, both genetic data and technological analyses of lithic inventories indicate that the initial phase of human colonisation from the south is followed by an influx, and possible mixing, of people from the east around the same time (Günther et al., 2018; Manninen et al., 2021). If this narrative is coupled with the data observed here, these migratory events could appear to result in a relatively sudden drop in site-count as indicated in the SSPD, which in turn could be related to a change in mobility patterns. The end of this drop also roughly corresponds to the first ^{14}C-dates in the RSPD around 8500 BCE, leading to the logistic growth that plateaus in the first centuries after 8000 BCE. The plateau of the logistic growth in the RSPD also has a corresponding positive deviation in the SSPD from the exponential model – an increase that was also noted by Berg-Hansen et al. (2022) – which could indicate that this demographic signal is reflected in the frequency of shoreline dated sites as well.

Subsequently, the SSPD deviates negatively from the exponential null from c. 6800 to c. 5800 BCE. This is followed by a positive deviation in the last centuries before 5000 BCE. These developments should possibly been seen in relation to simultaneous developments in the inland areas of southern Norway. The negative deviation in the SSPD appears to correspond to an increase in inland activity, which is to take place in the period from c. 6700–5900 BCE and reach its peak around 6200–6000 BCE (Boaz, 1999; Persson, 2018; Selsing, 2010). Boaz (1999) related this to an economic reorganisation, involving a more focused exploitation of the interior and a reduction in the utilisation of coastal areas. This period is followed by a marked reduction in inland activity, lasting until c. 4500–4000 BCE (Persson, 2018, p. 204), the onset of which thus corresponds to the end of the negative deviation in the SSPD at c. 5800 BCE, and the positive deviation from c. 5300–5000 BCE. Boaz (1999) associated the period of decrease in inland activity to the onset of the classic Nøstvet phase, which is now believed to commence in the middle of the 6th millennium BCE (Reitan, 2022). The Nøstvet period is argued to be characterised by an increase in specialised coastal adaptation that also coincides with what Fuglestvedt (2018, p. 17) has been termed 'the great wave' of rock art in Norway, starting from around

5700 BCE in south-eastern Norway (Fuglestvedt, 2018, pp. 42–46; Glørstad, 2010, pp. 216–233). The onset of the classic Nøstvet thus roughly corresponds with the positive deviation in the SSPD around the later parts of the 6th millennium BCE.

Directly relating these patterns to demographic developments or land-use and mobility patterns is challenging given the data available here. Given the stationarity of the logistic model of the RSPD after c. 7500 BCE, it is possible that fluctuations in the SSPD reflect variation in mobility patterns that are unrelated to demographic developments. There appears to be a negative deviation from the logistic null model in the RSPD corresponding to the one in the SSPD just before 6000 BCE. However, the logistic model could not be rejected for the RSPD, and so it is inappropriate to interpret any deviations from the Monte Carlo envelope and place any analytical weight on the deviations in the RSPD, at least given the present data. While it is possible that the fairly limited sample of ^{14}C-dates has led to an underestimation of this deviation, there is, additionally, no indications in the RSPD of an increased demographic signal in the period just before 5000 BCE (see also Solheim and Persson, 2018).

Given the presence of people and corresponding signal in the SSPD before the start of the RSPD, and the suggested relevance of mobility patterns for the lacking signal in the RSPD in this earliest period, neither proxy is presumably devoid of influence from population density or mobility patterns. This is also given support by the correspondence between the logistic growth in the RSPD and the positive deviation in the SSPD in the first centuries of the 7th millennium BCE. However, properly adjudicating this relationship and the degree to which it has held constant throughout the period will depend on independent data that track the developments of the other factors that have been suggested to be of relevance to the behaviour of the two proxies.

Another relevant point to mention here is that the relative sea-level change is effectively built into the Monte Carlo simulations, much in the same way as the Monte Carlo simulation method used with radiocarbon dates account for fluctuations in the calibration curve (e.g. Crema, 2022). The simulation envelopes therefore pertain to the frequency of shoreline dated sites that could be expected under the null models, given the distribution of sites in the study area (Figure 4A), the corresponding local trajectories of relative sea-level change (Figure 4B), and a constant relationship between sites and shoreline described by the gamma distribution employed for the dating procedure (Figure 2D). Beyond uncertainties to do with the dating method itself, and by extension also the generation of the Monte Carlo envelope, it is also conceivable that variation in rates of sea-level change has impacted settlement patterns beyond that which could be directly expected under these null models. An increased movement instantiated by increased rates of relative sea-level change could result in the transition to a settlement pattern involving more frequent moves than that which could be expected under a constant adjustment to the shoreline. If this is the case, the proxy would still reflect degree of occupational duration, but this could be a response to the rate of relative sea-level change rather than other cultural and societal dimensions such as migratory events or adjustments to other environmental developments. Directly accounting for variation in the rate of sea-level change could thus prove important for properly assessing the substantive implications of variation in this proxy.

6 Conclusion

This paper has presented a new methodology for assembling and assessing the sum of a large number of shoreline dates. This was done by employing the probabilistic method for shoreline dating presented in Roalkvam (2023a), and by drawing on analogous procedures in the treatment of the temporal frequency distribution of radiocarbon dates (Crema, 2022; Crema and Bevan, 2021; Timpson et al., 2014). The result of employing this methodology was then compared to radiocarbon dates from within the same area, to begin to assess the relationship between the two data types and their potential association with overall developments in population density and mobility patterns.

The main results were that the logistic model. This is characterised by a rapid logistic growth from the start of the RSPD, which plateaus and remains stationary from around 7500 BCE. This is contrasted to the shoreline dates, the development of which were better described by a function of exponential decay. While

this indicates that some process of decline in the number of shoreline dated has occurred over time, the model was rejected as an adequate description of the data. Some of the deviations from the model were then narratively explored to suggest some possible reasons for the nature and reasons for these deviations, but given the lack of a model that adequately describe the data, and the informal treatment of these deviations, these should be viewed as suggestions representing potential lines for further interrogation.

While it appears that the SSPD and RSPD are differentially impacted by population density, and, we cautiously suggest, the SSPD is more heavily influenced by land-use and mobility patterns, this suggestion and the nature of the discrepancy between the proxies clearly requires further investigation. Some lines of inquiry could be to also draw on lithic technology and tool-kit diversity as a function of population size and density (e.g. Berg-Hansen, 2018; Collard et al., 2013; Riede, 2014; Solheim et al., 2020), and mobility patterns that can potentially be inferred from the composition of lithic assemblages (e.g. Barton and Riel-Salvatore, 2014; Clark and Barton, 2017; Preston and Kador, 2018; Roalkvam, 2022), which is potentially also influenced by variable rates of relative sea-level change. In terms of mobility patterns, focus has been directed towards residential movement and occupational duration, but other dimensions relating for example to seasonal and territorial mobility could also prove to be important. In the same vein, environmental conditions, constraints and developments beyond relative sea-level change also represent a range of factors that can have implications for these dimensions, and will consequently be of future importance to unpack the relationship between the proxies (e.g. Jørgensen et al., 2020; Ordonez and Riede, 2022). Furthermore, aligning these different lines of evidence will also be dependent on a more direct modelling of the development in the SSPD, rather than simply basing the analysis on deviations from a rejected null model (cf. Timpson et al., 2021). Finally, mapping and contrasting these developments across a larger region will not only offer a larger sample size, which is especially limited for the ^{14}C-data, but could also provide important contextualisation for the developments observed here (see e.g. Lundström et al., 2021; Manninen et al., 2023).

Seeing as the method for shoreline dating implemented here was recently developed and has been subjected to limited evaluation and testing, there are still considerable uncertainties and limitations associated with its application. While we believe the approach represents an improvement over previous approaches, the results should therefore considered a cautions first exploration of the implications of employing a probabilistic method for shoreline dating when evaluating large scale trends in the temporal frequency distribution of coastal sites in the region.

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