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Inferring shellfishing seasonality from the isotopic composition of biogenic carbonate: A Bayesian approach

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ABSTRACT

The problem of accurately and reliably estimating the annual distribution of seasonally-varying human settlement and subsistence practices is a classic concern among archaeologists, which has only become more relevant with the increasing importance of holistic studies of social and ecological systems aimed at establishing deep historical baselines to ground current practical work in socioenvironmental management. In this paper, we present a novel approach to the analysis of shellfishing seasonality using stable isotope measurements on biogenic carbonate (e.g., mollusk shell). Our approach uses a Bayesian mixture model framework to construct an estimate of the annual distribution of shellfish harvesting activity (within some particular historical context) on the basis of isotope measurement sets from a sample of shell specimens (derived from some corresponding archaeological entity). This framework enables two major advances beyond current isotope sclerochronological methods for archaeological seasonality analysis: (1) flexible specimen-level seasonality assignments that may be as precise or diffuse as the data warrant and may respond to unforeseen seasonal signatures, unrelated to conventional seasons and perhaps only recoverable by mathematical analysis, and (2) full characterization of uncertainty accompanying the estimated density of shellfish harvesting activity at all points throughout the year, all of which may be displayed concisely in a single plot with an estimated density curve and uncertainty envelope. These features of our approach focus analysis and interpretation on the seasonally-varying human practice under study, as well as on exactly the state of our knowledge regarding the annual pattern of variation in that practice, including the portions of this pattern that remain poorly constrained. By treating these issues clearly, we address some common obstacles to the advancement of archaeological seasonality research, particularly as regards the appraisal of sampling adequacy requirements at various scales of analysis and the principled integration of diverse and possibly contradicting lines of evidence in broadly transdisciplinary research in the historical sciences. We hope that further elaboration of the methodological core presented here will aid the ongoing development of the creative and collaborative traditions of scholarship that have emerged around studying local and regional histories of social and ecological relationships, with the aim of healing and strengthening these relationships in the present and future.

Keywords: archaeomalacology, Bayesian statistics, historical ecology, mollusks, paleoclimatology, sclerochronology, seasonality, shellfishing, shells, stable isotope analysis, zooarchaeology

Introduction

Seasonal rhythms of settlement and subsistence are a long-standing concern of archaeological scholarship, with implications for a wide variety of research themes ranging across social-environmental dynamics (Prendergast et al., 2018), long-distance communication and political integration (Graeber & Wengrow, 2021), and the development of Indigenous intellectual traditions (Hadden et al., 2022). To detect seasonal rhythms in the archaeological record, archaeologists have employed numerous proxies, many based on recovering archaeological remains of seasonally-available plant or animal species, warranting inferences about both the seasonal utilization of the species in question and the seasonal occupation of the site (Monks, 1981). Besides seasonally-restricted species, archaeologists have often studied seasonality using biogenic structures (e.g., mollusk shells, fish otoliths) that are grown by accretion over the course of an organism's lifetime, allowing the investigator to fix the organism's season of death by establishing relationships between time of year and organismal growth rates and/or structures (e.g., Mellars et al., 1980; Clark, 1979) or geochemical signatures of seasonally-variable environmental parameters (e.g., Shackleton, 1973; Killingley, 1981).

This latter approach is of particular relevance for computational archaeology, as it relies on quantitative data (e.g., oxygen isotope composition [δ18O] of biogenic carbonate) for which statistical relationships have been established with environmental parameters (e.g., sea-surface temperature [SST]) whose patterns of seasonal variation may also be quantified (Kwiecien et al., 2022). However, despite the amenability of geochemical sclerochronological methods of seasonality determination to quantitative treatment, the standard for data analysis in these types of studies remains nonquantitative, erecting unnecessary barriers to the advancement of seasonality studies using these techniques. In what follows, we present a Bayesian framework for this style of quantitative seasonality analysis, focusing on the common case in which δ18O of biogenic carbonate (e.g., of marine mollusks) is used as a proxy for seasonal variations in SST (Urey et al., 1951). We first formulate the problem in general terms for a single specimen and then develop an approach to estimating the distribution of harvest intensity over the year by modeling the isotope measurement sets from a sample of archaeological shell specimens as a mixture of regression distributions relating time of year to oxygen isotope composition, with the harvest intensity at different times of year modulating the mixing proportions (Ferguson, 1983).

Our analytical approach advances the effectiveness and theoretical defensibility of isotope seasonality studies in two major ways:

1. It supports reliable detection of a wide variety of seasonality patterns by recording season-of-death estimates at fine resolution (days to weeks) and with full uncertainty characterization. We thereby avoid the risk of obscuring or distorting anthropologically-important seasonal contrasts that is inevitable under the common analytical strategy of dividing the year a priori into artificially coarse and arbitrarily positioned seasonal bins, chosen primarily for having visually-identifiable signatures in the annual SST curve.
2. It focuses attention on exactly what the analysis tells us about the seasonally-varying human practice of interest (including how the precision of our knowledge may differ at different points of the year) by reporting results in the form of an estimate of the annual distribution of shellfishing intensity that also quantifies the degree of uncertainty involved in different portions of this estimate. We thereby avoid the confusion around how much confidence should be placed in the results of a given study that arises from the common practice of reporting essentially just a description of the sample that the study in question has analyzed, rather than using that sample to make an inference about the theoretical population from which it was drawn.

The theoretical objections to shell seasonality studies that we answer here—regarding coarse, arbitrary seasonality assignments and unclear targets of inference and standards of evidence—were raised in essentially similar form by Claassen (1991) in her classic review of North American research traditions regarding shell-bearing sites. (Claassen's discussion mentions only growth-line seasonality studies, but the issues apply to isotope studies just as well; see Deith (1985) for a comparison.) Claassen attributes these problems to archaeologists' persistently simplistic treatment of both the structure of shell-bearing sites and the shell-depositing human practices involved in their development (see also Ambrose, 1967; Meehan, 1982; Waselkov, 1987). In the decades since, much work has been done within archaeology to improve the effective excavation and interpretation of shell-bearing archaeological sites and deposits (e.g., Stein, 1992;

Luby et al., 2006; Milner et al., 2007; Marquardt, 2010; Roksandic et al., 2014; Villagran, 2014; Letham et al., 2017), as well as the biological and ecological foundations and laboratory techniques of isotope sclerochronology (e.g., Kennett & Voorhies, 1996; Jones et al., 2008; Schweikhardt et al., 2011; Hallmann et al., 2013 ; Burchell et al., 2018 ; West et al., 2018 ; Jazwa et al., 2020 ; Kwiecien et al., 2022). However, little progress has been made in the final stage of data analysis, with current strategies generally employing a variant of either Shackleton's (1973) temperature-and-trend classification scheme (e.g., springtime is characterized by low SST that is increasing), Killingley's (1981) SST wiggle-matching approach, or some combination of the two (see, e.g., Hadden et al., 2022 ; Cuthrell, 2013 ; Burchell et al., 2018).

In paleoclimatology, researchers have made significant strides in the quantitative analysis of seasonally-resolved archives, including mollusk shells (e.g., Wilkinson & Ivany, 2002 ; de Brauwere et al., 2009 ; Ivany, 2012 ; Wang et al., 2015 ; de Winter et al., 2021 ; Kwiecien et al., 2022), but these methods are generally designed for the analysis of long-term, high-resolution data collected from a relatively small number of specimens (but see Zimmt et al., 2019, for a paleobiological counterpoint), with the aim of accurately characterizing variations in the seasonal climate regime over a long period. These techniques are therefore not particularly well suited to the needs of archaeological seasonality studies, which require a comparatively large number of specimens and are interested primarily in the final portion of the shell-producing organism's lifespan. This difference in focus warrants a different allocation of resources that increases the number of specimens per assemblage and decreases the number of samples per specimen, which is in fact reflected in the existing data base of isotope determinations from archaeological seasonality studies (see Palmer et al., 2022). (Note that the same is not generally true of paleoclimatic seasonality studies conducted using archaeological materials.)

The method we describe below is designed to fill this gap, allowing reproducible and rigorous quantitative analysis of the existing archaeological isotope seasonality database in a transparent fashion, while presenting a platform for further methodological development by incorporating more sophisticated anthropological, biological, depositional, and ecological process models increasingly under development. This approach also facilitates analysis of the larger samples necessary to address intra- and inter-site and diachronic variability, and offers a principle for combining the diverse lines of evidence that bear on settlement and subsistence seasonality, while properly accounting for the uncertainties of each.

In what follows, we present first a simple, computationally inexpensive method for estimating the death date (i.e., day of year) of a single organism, in order to outline the basic problem of seasonality determination clearly in statistical terms. We then describe a powerful approach to estimating the annual distribution of shellfishing intensity on the basis of an assemblage composed of many specimens, which makes use of a mixture model framework to characterize the uncertainty in our estimate of the distribution of shellfish harvesting activity over the year.

Methods

The present section will discuss the key features of our approach to statistical modeling of isotope-based shellfishing seasonality determination. For additional mathematical detail, as well as implementation of this modeling framework with fully reproducible scripted examples in R and Stan (R Core Team, 2023; Stan Development Team, 2022; Stan Development Team, 2023), please see the R Markdown document that accompanies this article (Lewis & Brown, 2023).

Estimating the season of death of an individual shell

Suppose we have a good regression model for the distribution of SST (y) over days of the year (w) at a given location, with parameters ϑ: $p(y|w, \theta)$. We also assume that the oxygen isotope composition of seawater at this location remains constant throughout the year, so that we may disregard the effect of ambient seawater $\delta^{18}O$ fluctuations on the $\delta^{18}O$ of carbonate precipitated in this environment (Epstein et al., 1951, 1953; Kim & O'Neil, 1997). Provided we are working with an organism with a reliable carbonate paleothermometer ($\delta^{18}O$ ~ SST) relationship so that parameter uncertainties can be disregarded, we are then essentially trying to predict the day of the year on which an observed SST time-series ended. For now, we do not model w, making $p(w)$ a uniform distribution. This choice is defensible only for the purpose of illustrating what we can learn from each shell individually. We assume that our regression is homoskedastic (equal variances in SST across different times of year) and make the large-sample approximation so that we can treat our parameters as concentrated entirely at their point estimates. We also stipulate that we know precisely the time-displacement between carbonate samples, equivalent to assuming a known constant shell growth rate throughout the year. None of these assumptions are strictly justified and can indeed be relaxed, but they do not trivialize the problem and add greatly to the ease of presentation for our purposes here.

We can then formulate a multivariate normal density function calibrated to the annual SST regression model and known spacing between carbonate samples, which will allow us to calculate the likelihood that a hypothetical organism dying on a given day would produce a particular SST time-series: $p(y = y^*|w^*)$. This likelihood can then be 'inverted' by summing over all possible death-dates to yield the probability that a real sampled organism producing an observed SST time-series in fact died on a particular day:

(1) $$p(w^*|y = y^*) = \frac{p(y=y^*|w^*)p(w^*)}{\int p(y=y^*|w)p(w)\,\mathrm{d}w}$$

Estimating the annual distribution of shellfishing activity

We would like to go a step further and do away with the theoretically indefensible practice of treating each shell as though its death was influenced by an entirely unique set of causes. Instead, we would like to learn precisely about the common causes involved in the death of all shells in an assemblage from a given place and time, i.e., the human practices of seasonally-varying shellfish harvesting activity. So, we model w explicitly, so that we are working with the full joint probability model: $p(y, w|\theta, \lambda) = p(y|w, \theta)\, p(w|\lambda)$, where λ represents the parameters of the prior distribution of harvest intensity over the year.

For each shell i, we have n_i observations ordered in time. Each observation $(y^j_i,\Delta w^j_i)$ comprises a temperature y^j_i which occurred at some time w^j_i that is unobserved; we observe only the corresponding time-displacement $\Delta w^j_i = w^j_i - w^{ni}_i$, where w^{ni}_i is the unobserved time-of-harvest. We will assume that temperatures are normally distributed around a sinusoidal mean-function $\mu(w_i,\vartheta)$ with some covariance $V(w_i,\vartheta)$: $p(y_i|w_i,\vartheta) = N(y_i|\mu(w_i,\vartheta),V(w_i,\vartheta))$. The joint probability distribution of the data then is:

(2) $$p(y_i,\Delta w_i|\theta,\lambda,\gamma) = \int p(y_i|\Delta w_i,w^{ni}_i,\theta,\lambda,\gamma)p(\Delta w_i|w^{ni}_i,\theta,\lambda,\gamma)p(w^{ni}_i|\theta,\lambda,\gamma)$$

The displacements Δw_i and final time w^{ni}_i together contain exactly the same information as the times w_i themselves, so $p(y_i|\Delta w_i,w^{ni}_i,\vartheta,\lambda,\gamma)= p(y_i|w_i,\vartheta,\lambda,\gamma)$. We stipulate that $y_i|w_i$ is indeed modeled using only the regression parameters ϑ: $p(y_i|w_i,\vartheta)$. We then assume that the marginal distribution of harvest-times has its own parameters λ which do not include the other parameters and also, as above, that the displacements Δw_i are fully determined by w^{ni}_i and a known spacing-vector γ_i. Thus, $p(\Delta w_i|w^{ni}_i,\vartheta,\lambda,\gamma)$ effectively drops out of the integration and we can dispense with the parameter γ:

(3) $$p(y_i,\Delta w_i|\theta,\lambda) = \int p(y_i|\Delta w_i,w^{ni}_i,\theta)p(w^{ni}_i|\lambda)$$

Suppose we know there are arbitrarily many possible harvest-times w°_j, where j=1,...,J, with corresponding probabilities λ_j. The data-generating distribution is then a finite mixture of regression distributions, mixing over possible harvest times w°_j with probabilities λ_j:

(4) $$p(y_i,\Delta w_i|\theta,\lambda) = \textstyle\sum_j p(y_i|\Delta w_i,w^\circ_j,\theta)\,\lambda_j$$

Each probability λ_j may be interpreted as the harvest intensity at time w°_j, so inferences about λ_j are of primary interest. All that is required further is to place prior probability distributions on ϑ and λ and translate the model into Stan to draw samples from the posterior distribution of λ.

Note that we may still draw inferences about individual shells. For each posterior draw of λ, we simply calculate:

(5) $$\Pr(w^*_i=w^\circ_k|y_i,\theta,\lambda) = \frac{p(y_i|w^\circ_k,\theta)\lambda_k}{\sum_{j=1}^{J} p(y_i|w^\circ_j,\theta)\lambda_j}$$

We can see from the above expression that we may still draw fairly precise inferences about an individual shell even if the harvest distribution (described by λ) remains largely unknown.

Results

A full quantitative assessment of the performance of the above methods will await their testing on a range of both real-world and simulated datasets (cp. de Winter et al., 2021). For now, we will just describe the basic successful operation of these tools and some of the desirable attributes of the results produced. The results and figures discussed are available in full detail, along with reproducible generating scripts, in the R Markdown document that accompanies this article (Lewis & Brown, 2023).

The procedure for drawing inferences about a single shell described above allows us to do a similar kind of analysis as has for decades been the standard in archaeological applications of isotope sclerochronology, in which a set of isotope measurements from a specimen is compared to the pattern of seasonal variation in a relevant environmental variable in order to infer the time of year at which the organism died and shell growth ceased (Fig. 1). However, our results improve upon the current state of the art in several important ways. First, the assumptions on which the analysis is based are made explicit and all steps are automated so that the entire analysis is reproducible and much more time-efficient than visual analysis of each set of measurements. The analysis is also statistically modeled so that results may be reported with proper characterization of uncertainty, which more faithfully and flexibly conveys what can be learned about the specimen's season of death, while simultaneously removing the need for any a priori delineation of coarse seasonal bins of potentially questionable anthropological relevance. Additionally, by modeling the set of isotope values likely to be recorded under a particular shell carbonate sampling strategy (e.g., samples drilled at 0 mm, 1 mm, 2 mm, and 2.5 mm from the shell terminus) as a multivariate normal distribution, we employ *all* of the data we have toward inferring the specimen's season of death, as opposed to the analytically inefficient practice of collapsing the data in some way in order to make it tractable for nonstatistical visual or semi-quantitative analysis (see, e.g., Culleton et al., 2009; Mannino et al., 2011; Eerkens et al., 2013; Hadden et al., 2022).

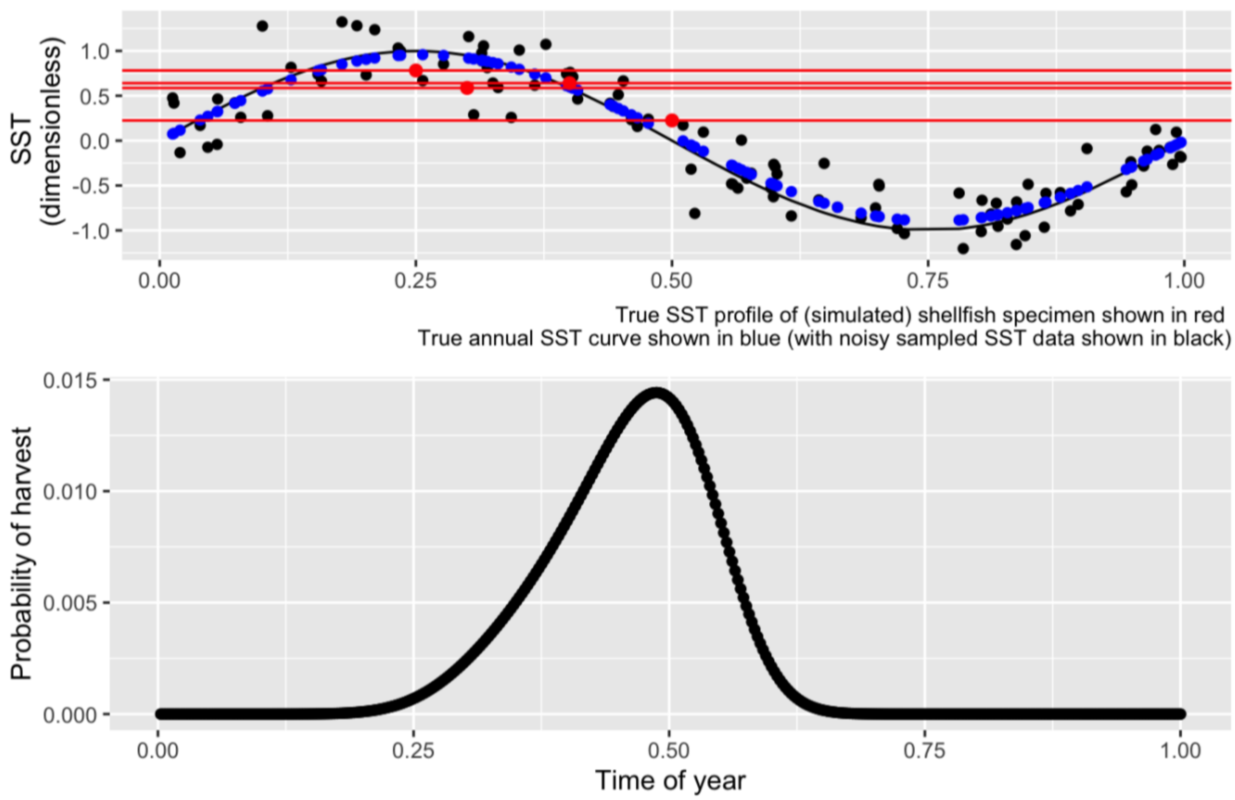

Figure 1 — Estimating mollusk death date from multiple isotope measurements at intervals along shell growth axis.

The procedure we present for analyzing a sample of multiple shells in tandem explicitly to construct an estimate (with uncertainty) of a population distribution of interest apparently has no equivalent in the literature on isotope sclerochronology for season-of-death determination. All other studies that we are aware of derive their inferences about samples of multiple shells (and only implicitly the larger statistical populations they represent) just by tabulating and aggregating individual determinations of season of death on single specimens. This strategy is needlessly conservative: archaeologists study not one but many archaeological shells because we believe at least some of them to have been harvested according to some shared set of practices common to a human group at some place and time. Therefore, we should pool all specimens that we believe to have been harvested under related conditions and study them collectively, using all of this data to constrain the parameters of the population distribution from which we understand this sample to have been drawn. It is this style of analysis that our method enables and encourages, which offers both greater inferential power and a sounder theoretical underpinning than the alternative. Figure 2 shows the results of a run of the mixture model described above using simulated data (shown in the upper panel). The estimated annual distribution of harvest intensity (lower panel) matches both the sample and population distributions of shell death dates quite well. The uncertainty (shown in gray) represents how tightly constrained by the data our estimate of harvest intensity is during different portions of the year. Note that our uncertainty-bounded *estimate* of the population distribution of season of death is a better characterization of the true population distribution than is even the *true* sample distribution, not to mention the estimate thereof that we could construct in a real-world case.

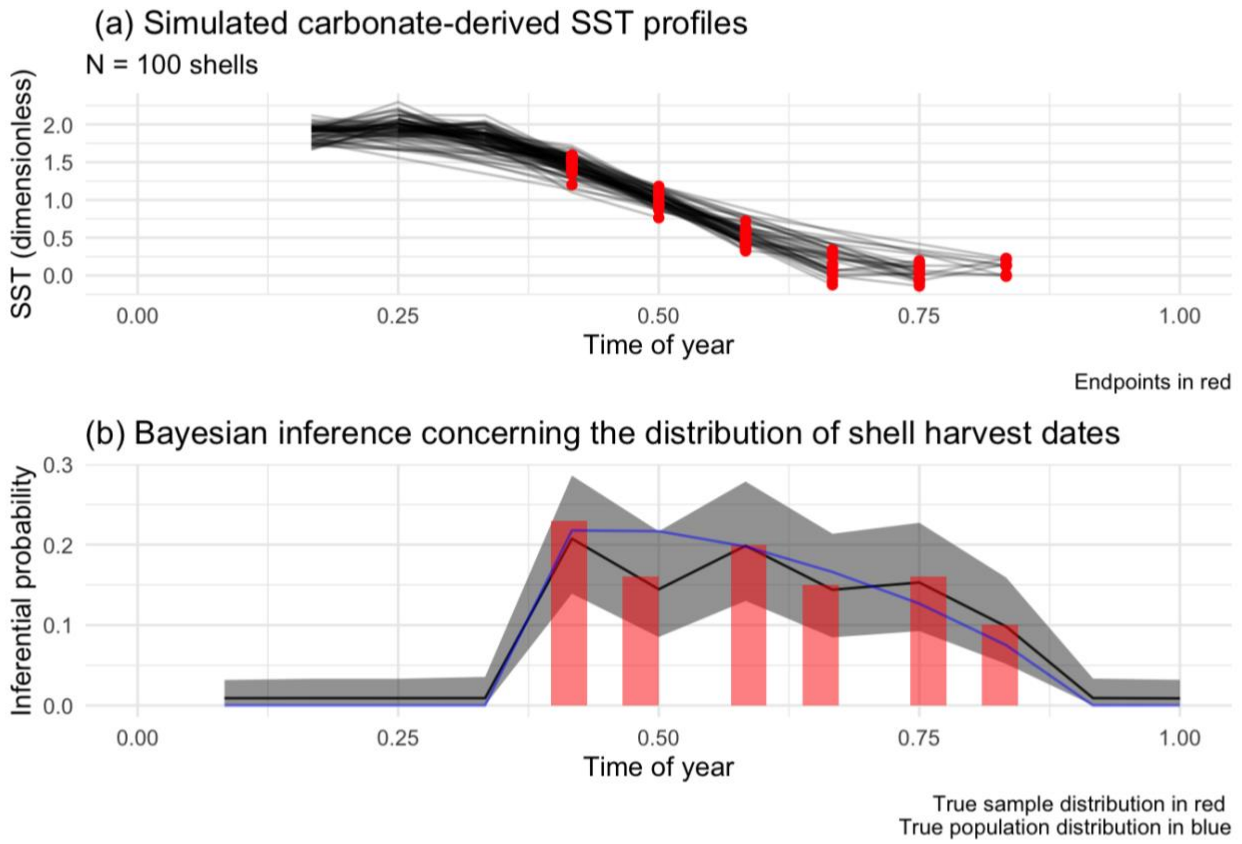

Figure 2 — Estimating the annual distribution of shellfishing activity.

Discussion

The key contribution of these results is to demonstrate the feasibility and value of deriving carbonate isotope composition-based estimates of subsistence (or settlement) seasonality that both characterize seasonal signatures with full flexibility and also transparently report the (nonuniform) uncertainty envelope around the estimated seasonality distribution. These features are essentially the usual merits of a fully modeled (esp. Bayesian) statistical approach, in which the processes understood to be responsible for generating the data are clearly described in quantitative terms, making plain the relationship between the sample of observations submitted to analysis and the unobserved (and here unobservable) statistical population from which this sample is understood to have been drawn. By defining the theoretical population explicitly, it becomes possible to assess the extent to which the sample is adequate to confidently characterize the population parameters of interest, a problem that has affected archaeological isotope seasonality research throughout its history (see Claassen, 1991) and still presents difficulties today. Without a clear statistical framework, uncertainty as to what would constitute an adequate sample size (i.e., number of specimens) has often led conscientious researchers to follow the practice of paleoclimatologists and opt for fewer specimens with more isotope measurements per specimen, in order to increase confidence about season-of-death assignment per specimen (e.g., Hallmann et al., 2013; Burchell et al., 2018). Our method offers some balance to this tendency by quantifying analytical uncertainty at the level of both the specimen and the assemblage in order to find the most efficient strategy to reduce the overall uncertainty about the target of inference (e.g., the seasonality of shellfishing practices of a community at a particular place and time) in the case in question, facilitating better planned and even multi-step adaptive sampling programs, such as that implicitly described by Bailey et al. (1983). The transparent characterization of uncertainty in our approach also helps to ameliorate the common issue of isotope seasonality determinations appearing to contradict other sources of seasonality evidence, particularly historical and ethnographic (e.g., Jones et al., 2008; Hallman et al., 2013). With a clear sense of the precision of the isotope seasonality analysis, researchers have a straightforward path to reasoning about possible compromises between evidentiary bases with differing strengths or ranges of application.

An additional benefit of the population-oriented method we present is that it may also be applied to different groupings of the same set of specimens (including the extreme case of studying each specimen separately), in order to use isotope seasonality evidence to inform delineation of archaeologically-relevant units of study for other purposes. This 'reverse' application is one example of a variety of potential uses for this methodology within the diverse inferential ecosystem of archaeological research (see Wylie, 2002; Currie, 2018). Brown (in press) discusses these potential applications in more detail, describing how they relate to what are often viewed as sources of deleterious uncertainty by researchers seeking seasonality determinations. For example, though temporal variation in mollusk shell growth rates complicates the determination of season of death (Schöne, 2008), this fact also implies that, if season of death can be established with some certainty (e.g., by fixing on some clear cultural pattern of shellfish harvesting), then we may be able to use this information to learn about growth rate variation in a species or population under certain conditions. This goes somewhat further than the admirable recognition by paleoclimatologists of the potential climatological value of isotope measurement datasets produced originally for archaeological seasonality-determination purposes (e.g., Palmer et al., 2022): not only may the data be mobilized to different ends, but rather the data can most fruitfully be viewed as the complex outcome of a range of diverse processes (climatological, biological, anthropological, etc.), which are nevertheless intimately connected and about which it is precisely these interconnections that are turning out to be most interesting and worthy of study, often with some sense of urgency (Prendergast et al., 2018; Kwiecien et al., 2022).

By extending the core model presented here with additional components treating the quantitative impacts (and uncertainty) of organismal physiology and ecology, subannual autocorrelation of climate time-series, interannual climatic variation, paleoclimatic and paleoenvironmental reconstructions, and knowledgeable modification and development of subsistence and settlement strategies by local human communities, we can create the opportunity to learn across these diverse systems, all of which are understood with varying levels and types of uncertainty. It is this sort of holistic, omnivorous (sensu Currie, 2018) approach to research that characterizes archaeology at its best (Wylie, 2002) and especially the specific tradition of Indigenous-led eco-archaeological scholarship from which the work presented here ultimately derives (Lightfoot et al., 2021). Some tentative steps toward demonstrating how a fully modeled quantitative treatment of the isotope seasonality problem can provide benefits for a wide variety of different research themes are taken by Apodaca et al. (in press), applying the method detailed in Brown (in press) to the study of mollusk isotope data from three sites in Santa Cruz County, California, particularly with regard to physiological and anthropological processes (e.g., choice of shellfish gathering location) that interact with the seasonality determination problem. Brown's (in press) method differs from that presented here, in that it is based on measuring the correlation of an individual specimen's isotope measurement profile with portions of an empirical historical SST seasonality database and constructing only a 'point' estimate of the annual distribution of shellfishing activity without characterizing uncertainty around this estimated distribution. However, it still shares some of the essential features of the method described above, namely, allowing fully flexible high-resolution seasonality estimates (i.e., without preselected coarse bins) and reproducibly incorporating assumptions regarding biological, climatic, and environmental variables into the analysis, thereby allowing for sensitivity testing and exploration of the relationship between these assumptions and the seasonality conclusions reached.

The substantially more powerful Bayesian framework presented here can be extended much further in a similar direction, to holistically address larger questions of rhythmic interactions between biological and environmental dynamics and communal human traditions and innovations regarding the management of social and ecological systems (Hadden et al., 2022), as well as the more narrowly disciplinary concern of synthesizing a wide variety of seasonal and temporal indicators across the history of settlement at an archaeological site or within a region (Monks, 1981). Such study of complex human eco-management systems articulates well with the distinct but allied goals of paleoclimatologists working to refine high-resolution studies of individual archives (de Winter et al., 2021), simultaneously offering a window onto the spatial and temporal structure of human engagements with dynamic environments (Prendergast et al., 2018). Many published datasets already exist that could support such large-scale research aims (Palmer et al., 2022), but for problems of comparability between different sample sizes and sampling routines that are difficult to resolve without a clear statistical formulation of the research problem (Claassen, 1991). The explicitly statistical method presented here allows us to leverage these legacy datasets without costly physical reanalysis, while also providing a way to update analyses with the latest high-resolution results. We hope that such retrospective and summary-oriented application of this framework in the near future will provide guidance for the planning and development of integrative, transdisciplinary work on biogenic recorders of seasonal cycles and with (and on behalf of) the anthropogenic archives—such as archaeological sites conserved within important and often sacred places of Indigenous peoples—in which they are catalogued and held.

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Data, scripts, code, and supplementary information availability

Scripts are available online (in R Markdown format with explanatory text and annotations): https://doi.org/10.5281/zenodo.7986873 (Lewis & Brown, 2023).

Conflict of interest disclosure

The authors declare that they comply with the PCI rule of having no financial conflicts of interest in relation to the content of the article.

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