Archaeological and Anthropological Sciences (2024) 16:154
https://doi.org/10.1007/s12520-024-02056-8

REVIEW

A current assessment and commentary on the field of shell seasonality

Niklas Hausmann[1]

Received: 4 March 2024 / Accepted: 1 August 2024 / Published online: 2 September 2024

Abstract
This review aims to summarise the outcomes, methods, and ideas of shellfish seasonality studies of the last 50 years. With the start of using mollusc shells as indicator of seasonal subsistence and mobility, a range of methods and approaches were used to better understand past human use of the marine (and riverine) environment. I have collated information from over 70 studies and over 400 sites to provide and compare information regarding their seasonality, their spatial and temporal distribution, their species of interest, their sample sizes and methods of determining season. In addition, I have selected several case studies that spotlight and emphasise ideas and important aspects of seasonality research which are worth reintegrating into current studies, chiefly among them the reliance on adequate modern reference studies. I further show that even today, the time investment and general lack of modern and local reference studies are one of the major problems in the study of shell seasonality.

Keywords Coastal Archaeology · Seasonality · Sclerochronology · Molluscs · Review

Aims and scope

The study of molluscs or shell middens in archaeology has seen quite a few review papers over the last decade, going into much detail about new methods, current research trends, and the general increasing interest in this very multidisciplinary field (Prendergast and Stevens 2014; Thomas 2015a, b; Twaddle et al. 2016; Leng and Lewis 2016; Allen and Payne 2017; Kwiecien et al. 2022; Mannino and Thomas 2023; Rick 2023; Robson et al. 2023). Few of them looked at the early beginnings of shell-seasonality to draw conclusions about how the field has changed since then. Of course much has changed, that has chiefly to do with how archaeology as a discipline changed: studies become more international, more multidisciplinary, more technologically specialised. As such, some of the major studies of the 20th century would now be seen as outdated and should potentially undergo a thorough methodological reassessment. But there is much to gain from looking at how the changes in methods of shell-seasonality between then and today have had an impact on the scope and the robustness of the studies and to see what limits or ideas were struggled and experimented with back then, to see how we can apply or solve them today.

✉ Niklas Hausmann
niklas@palaeo.eu

1 Leibniz Zentrum für Archäologie, Ludwig-Lindenschmit-Forum 1, Mainz 55116, Germany

Interestingly, many aspects of determining seasonality using the technologically more advanced geochemical data are very similar to doing it via simple (or elaborate) growth incremental analysis and many of the questions between the methods are similar too: One uses modern references from different seasons and uses those data or images to group the archaeological ones based on their similarity with the modern seasons; once the specimen's season is determined, it gets extrapolated to interpret some or all of the assemblage. Alas the scale on which seasonality studies operated in the past, vastly exceeds our current studies using stable isotopes. So I collected information from publications that also include this earlier part of shell-seasonality research to see what we can learn from them. Additionally, I want to spotlight some studies from the 20th century, to pick up some ideas again, that we might have abandoned or simply never known about, with the aim to induce even more archaeological and modern reference research in the subject and to empower those who quite rightly say that there is much yet to be known about shell seasonality and species variability before we can confidently and unquestionably rely on it.

Data foundation

I have compiled a list of studies that used mollusc remains to determine season of capture and to answer questions of this kind of seasonality, as opposed to seasonality in terms of climatic conditions (Kwiecien et al. 2022), within archaeological sites. This list is limited by my own language skills (English, German), the findability of papers not in those languages, so that they can be translated, and what I was able to access myself. That said, some studies, which I could not access, were summarised by others and are included. Nevertheless, the information that was accessible to me is incomplete and might well overlook some larger trends that I was simply not aware of. I hope that in the future, other traditions of mollusc seasonality studies will be added to this list of publications and might point towards other developments. The data itself is archived open access as an Open Science Framework (OSF) repository and within a GitHub repository[1] so that it can grow in the future (Hausmann 2024).

From the gathered material, information was of significance was compiled or that was likely to show long-term or spatial trends. This information includes the general location, the method of analysis, the analysed species, whether it was marine or freshwater species, whether there are modern references available, whether the occupants were hunter-fisher-gatherers and/or farmers, whether they were sedentary or not, what period the site dated to and what kind of deposit included the shells (e.g. midden, mound, layer). With this information I was hoping to find out more about the general site types and environmental settings where seasonality studies are carried out.

I was also interested in what I would consider indicators of quality or robustness, such as the numbers of shells and layers analysed vs the number of layers at the site, also the number of terminal edge samples in geochemical analyses and the number of years within the record. With this information I was aiming to find trends or patterns in the scale and representability of the individual studies.

Lastly, I wanted to find out more about the questions that were asked of the shells. Seasonality lies at the core of the questions, but context provides interesting opportunities to draw specific conclusions. In this context I also collected the general result of seasons indicated, although that was not always directly comparable due to the different seasonal make up of the local environment and the various degrees of accuracy of the specific methods.

General overview

Before going into details, I want to present the dataset in general. There are 73 studies with an arbitrary cutoff point of 2020, which total 418 individual sites. These studies are unevenly distributed across the globe (Fig. 1). Some obvious biases are apparent with much of the information coming from North America. This might well be because these publications were more accessible than others. On the other hand the long research history of shell middens, their extensive and dense concentration along the American shoreline and their use into recent times, makes them a generally accessible site type for North American archaeologists, which might well explain the large number. The distribution by studies is also mirrored in the distribution of sites: Atlantic North America (210), Pacific North America (65), Atlantic Europe (27), Mediterranean (19), East Asia (29), Other (9), Oceania (10), South America (4). More about the large amount of Atlantic North American sites below (Section Growth incremental studies of the US).

The earliest study I found was by Margaret Weide (1969), which I did not access myself but which is frequently quoted and which is described in some detail in the doctoral thesis by L.C. Ham (1982). Claassen (1990) also mentions Paul Chace as having worked on the same topic and site, but I could not find a publication related to that research. Interestingly, the second study I found came from New Zealand (Coutts and Higham (1971)), where shell middens are also an extremely common site type.

Since then seasonality studies have been published consistently with an increase of studies in the last 15 years with up to eight in one year (2014) (Fig. 2). But that increase is somewhat misleading and by no means mirrored in the number of sites or amount of work put into the studies themselves as is illustrated by the number of sites included in each published study. Studies comparing seasonality results across many archaeological sites rather than presenting the seasonality data from one site only, were much more common during the 20th century. This pattern has to do with the preferred method of determining seasonality and how e.g. growth incremental analysis allows one person to study many more shells than e.g. stable isotope analysis does. As such, publications including dozens of sites were more common in growth incremental studies than in those using stable oxygen isotopes, which have become more common in the 21st century. I can also not rule out that in some cases one site was part of multiple studies and thus counted twice, as it was not always clear whether the entire data was new or parts reported from an earlier study.

Research methods

Shellfish seasonality has seen a range of methods of analysis. They vary often from one study to the next, depending on the shell anatomy, sample availability, and the research question. Generally, these methods can be grouped into the measurement of growth patterns of the shell, both **externally** and **internally**, biogeochemical methods, such as **stable oxygen isotope ratios** or **trace elemental ratios** (usually Mg/Ca), and lastly the shell size. Each method has its strengths and limitations depending on the steps involved. For instance,

[1] https://github.com/Niklas-palaeo/ShellSeasonalityReview

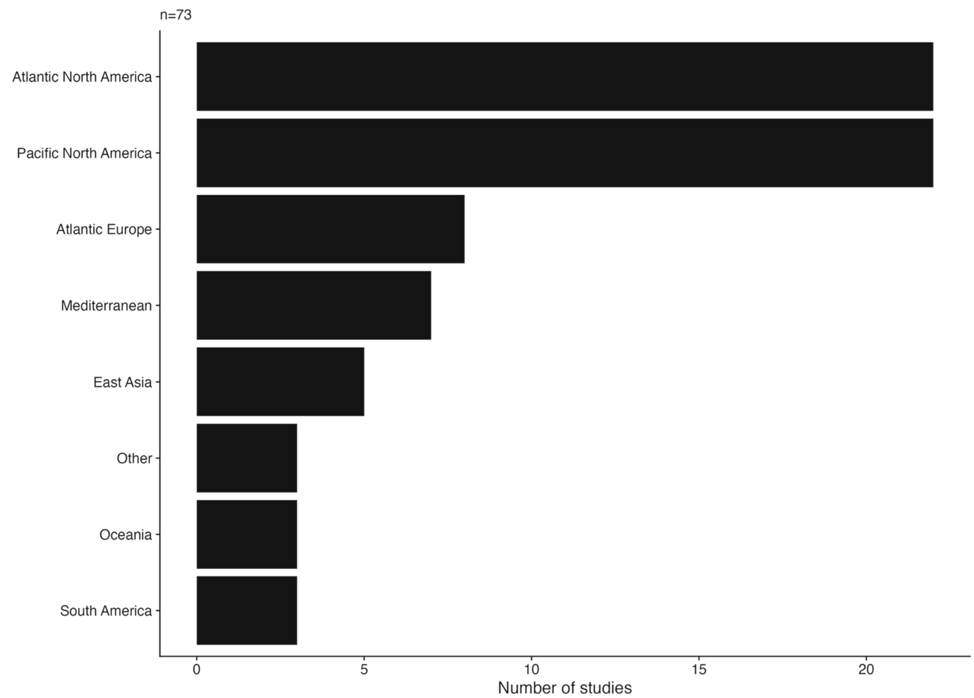


Fig. 1 Spatial distribution of studies. The category 'Other' includes South Africa, Saudi Arabia and inland North American Sites

shell size only requires the measurement of the shell length (or other anatomical feature), which can be done within seconds, at little cost, and with almost no prior experience. On the downside, this method ideally requires molluscs that only live for one year and grow predictably throughout their short lifespan, otherwise the overlap between multiple years and their seasons leads to much inaccuracy in the final assessment of the overall seasonality. Because growth is non-linear and

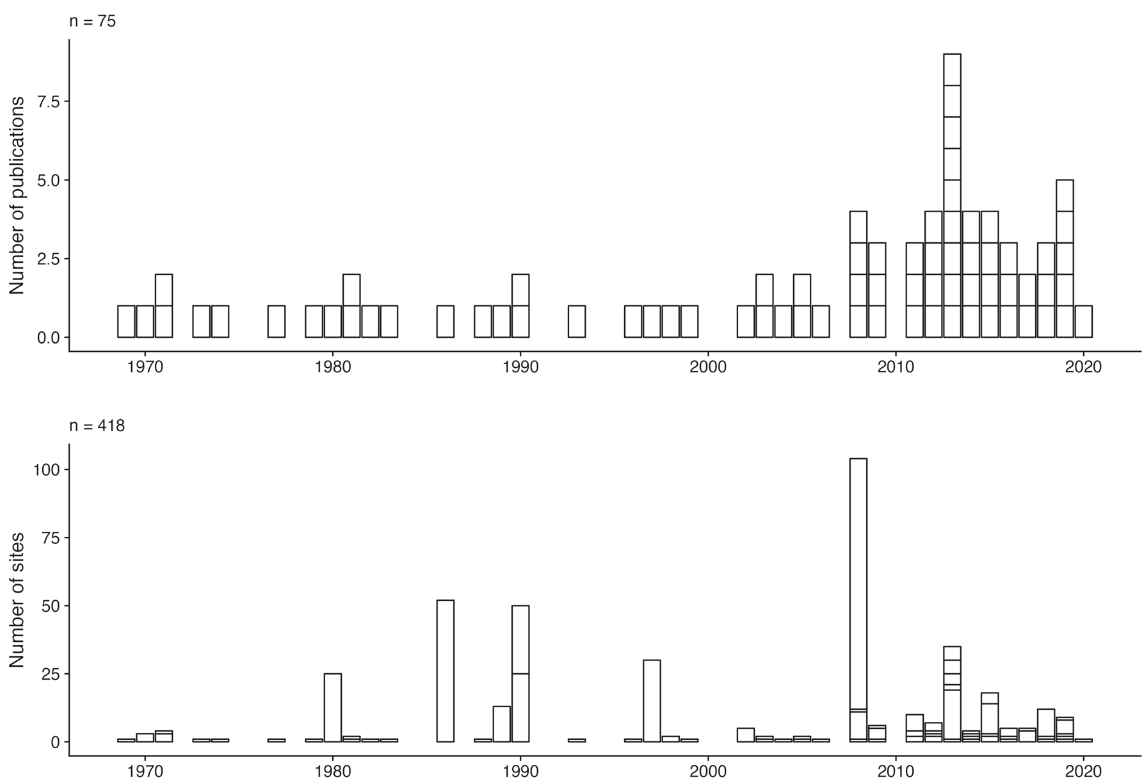


Fig. 2 Quantities of publications and sites in each year. Major studies in the dataset also group work by others and are not always the work of one person only

slows with age, this method can become increasingly inaccurate the longer the lifespan of the mollusc is. Either way, the quality of the modern reference collection is tantamount to the success of the method (Keene 2012). Measurement of the external growth patterns is a similarly straightforward method, as it only requires some training, and can be carried on species, that live multiple years. For this method, one usually establishes through modern references the number or size of growth increments visible on the shell exterior, at the time of a specific season. Commonly, annual increments or growth features are split into seasonal stages of development to which the archaeological specimens are then matched and their season of death determined. A significant drawback of this method is the large variability of growth between specimens as well as within one specimen. Even when features are measured not just by eye but instrumentally and these measurements studied statistically, their predictions are generally too imprecise to rely on Claassen (1988). The measurement of internal growth lines allows a more detailed view of the annual and seasonal growth stages of shells to more confidently describe the stages of shell development through time (Milner 2001). This can happen on varying resolutions, with some counting tidal growth increments on a high-resolution (Hallmann et al. 2009) and others only annual periods of fast or slow growth on a low resolution (Quitmyer et al. 1985). Shells need to be sectioned beforehand, usually using a slow-speed saw through the largest extent of growth or specific features that contain the entire growth record (e.g. oyster hinges). Subsequently, they require grinding and polishing as well fastening onto glass slides. Each one of these steps is time and labour intensive — especially as the method requires a robust sample size — giving it a disadvantage compared to the previous studies. As is the case for the above methods, modern reference shells, which also need to be sectioned, ground and polished, provide the comparative baseline. Both internal and external growth structures are however very specimen-specific and the variability of growth rates, growth periods, and growth-impacting events (e.g. stress due to injury or reproduction) further complicate the assessment of the season of death (Schöne 2008b). This is why current research standards rely on more objective measures such as the biogeochemical evidence for specific seasons that is mainly externally controlled (West et al. 2018). Biogeochemical methods further characterise the growth increments using stable isotopes or trace elements as proxies for seasonally changing environmental factors such as sea surface temperature (Kwiecien et al. 2022). The advantage of this method is that the results provide a reliable insight into the season of death but also the environmental context at the time. Major downsides stem from the investment of time and money as each shell needs to be sequentially sampled for carbonate powder, which is then analysed through equipment that not every department or institute has access to (see also *Managing isotope costs*).

For this review, the methodological approaches were grouped into the categories of **external patterns**, simple internal **growth incremental analysis**, and also **high-resolution growth incremental analysis**, which requires the use of microscopes, then the analyses of **stable oxygen isotopes** ($\delta^{18}O$) and of **magnesium to calcium ratios** (Mg/Ca) (Fig. 3). Internal methods were split because high-resolution growth incremental analysis, commonly focuses on daily or tidal increments, which provide a more accurate resolution, compared to studies that look at species-specific growth bands or annual increment widths, which are much more variable (Hallmann et al. 2009; Zimmt et al. 2019). Despite the wide range of approaches applied in the field, these groups of methods encapsulate well the degree of effort in time and costs that need to be invested into the analyses. This way the studies' various focuses on how efforts were made and to what goal, become more comparable.

Growth incremental analyses have a healthy lifetime with almost 200 sites being analysed almost continuously with no major gaps. External patterns have been used as well to determine seasonal growth stages, but their use has stopped in the late 90s, most likely due to the errors that come with them (Surge et al. 2001; Zimmt et al. 2019). Size-measures are somewhat of an outlier. They have recently been applied to very short lived *Boonea impressa* shells, which predictably grow over the course of only one year so that their size can be attributed to a season. They themselves were not collected for consumption but were attached to oysters that were. While the approach is ingenious, as it uses the characteristics of a parasitic mollusc to determine the season of death of the host mollusc, the method is not widely applied, due to inconsistencies in the population structure and unclear influences of environmental factors (Keene 2012).

Interestingly, growth incremental analysis and geochemical analysis both turn up at around the same time. However, geochemical methods did not really take off until the end of the 20th or rather the beginning of the 21st century, due to the investment of cost and time (Monks 1981). Nevertheless, costs did not prevent the relatively early publication of the first study using stable oxygen isotope values specifically to determine the season of death, published by Nick Shackleton in (1973). In fact, he announced the potential for this work even earlier (Shackleton 1970) and was aware that having access to a laboratory that can carry out the analysis, put him into the very privileged position to do so. Somewhat earlier and working in the same lab on the site of Haua Fteah, Emiliani (1964) looked at sea surface temperature from archaeological shells but not specifically at the season of death. Comparing the methods used in seasonality studies, I also wanted to look closer at how the various methods

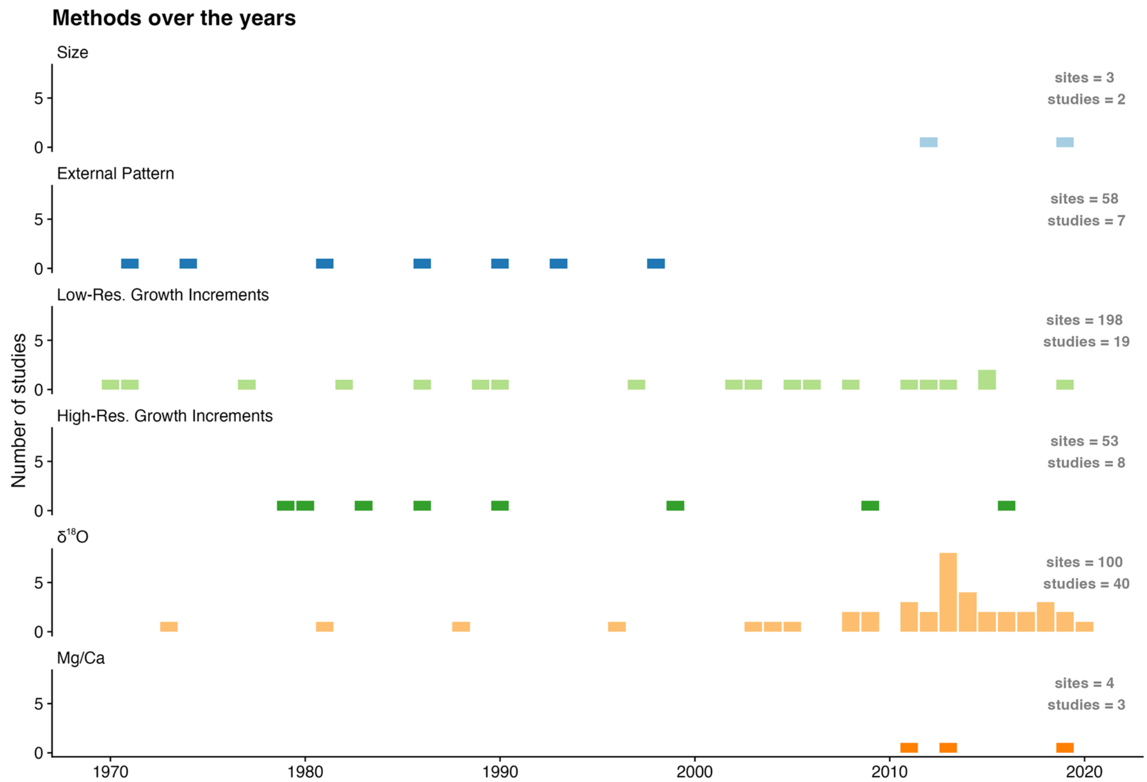


Fig. 3 **Overview of methods** through time with a total number of studied sites indicated by method

allowed for different numbers of specimens to be analysed per study (Fig. 4).

Not too surprisingly, less time-intensive methods allow for more specimens, with some studies pushing the limits into the thousands, when only external patterns were analysed. But that is not always the case and several methods reach multiple hundreds of shells per site. That said, a straightforward method also does not guarantee its reliability nor large sample numbers, as these are also depending on sample availability and preservation, as well as how focused the overall research is on seasonality.

Elemental analysis of Mg/Ca ranges fairly high given that it involves expensive laboratory equipment. The data here is mainly driven by two publications (Schweikhardt et al. 2011; Finstad et al. 2013) that carried out edge-only sampling for Mg/Ca ratios and δ^{18}O-values. The combined approach of elemental and isotope ratios shows a seasonal cycle of different combinations of both proxies (δ^{18}O and Mg/Ca, low/low: winter, low/high: spring, high/high: summer, high/low: autumn). Both datasets derive from one carbonate sample simply removed from the outside of the shell, which does not require time intensive sectioning. Other studies (e.g. Hausmann et al. 2019) do require sectioning and are thus showing lower specimen numbers.

Modern local references

For almost all seasonality archives, a well-understood reference sample and related environmental information is required to establish the way that different seasons are shown in the archive, so that this relationship can be extrapolated to past archives. However, this is not always the case because modern references are not always accessible or the planning of the study did not allow for a pilot study of the general functioning of the seasonal archive. Often a study of the same archive but elsewhere is referenced, which is getting more and more common, as seasonal archives become established. Overall, of the 418 sites, 73 (18%) did not have such an archive with 11 (3%) not providing any information and the majority (334, 80%) relying on modern pilot studies, albeit not always local.

Species

The most common of the analysed species are clams of the genus *Mercenaria*, which I have looked at depending on how many sites have been analysed with this genus (Fig. 5). These statistics are often not the best way to present an unbiased

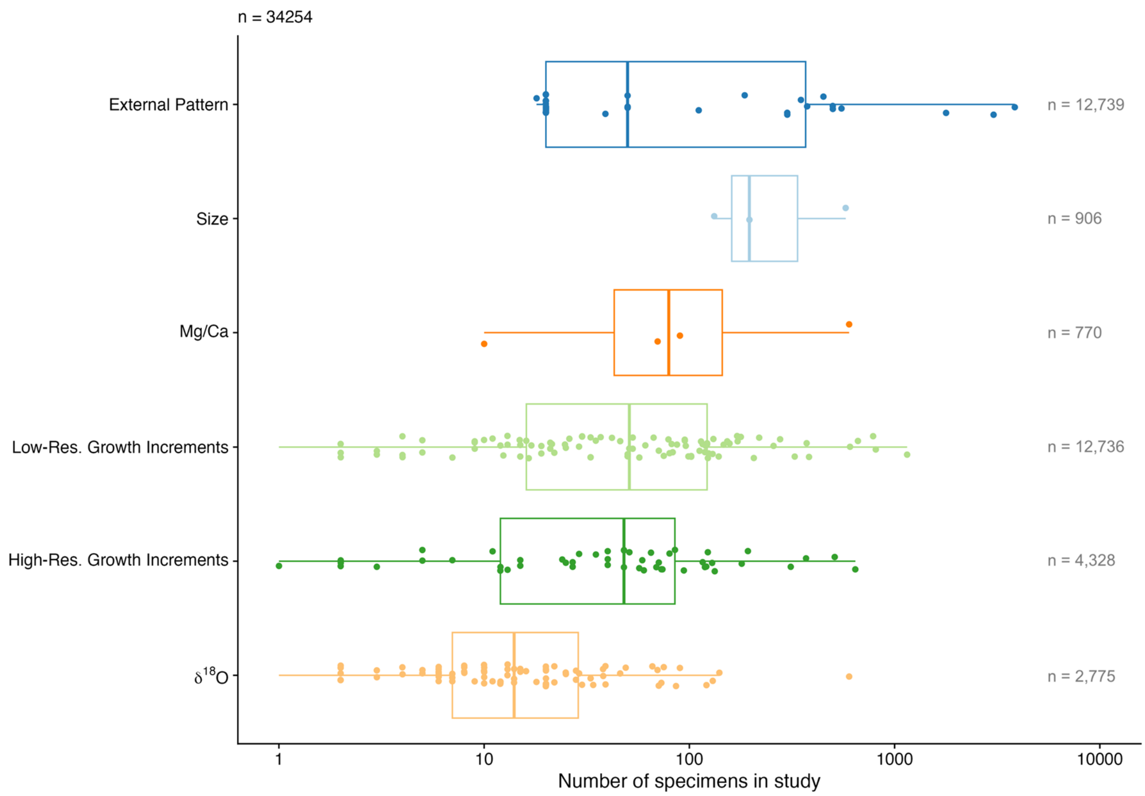


Fig. 4 Quantities of specimens by method Note that the x-axis is on a logarithmic scale

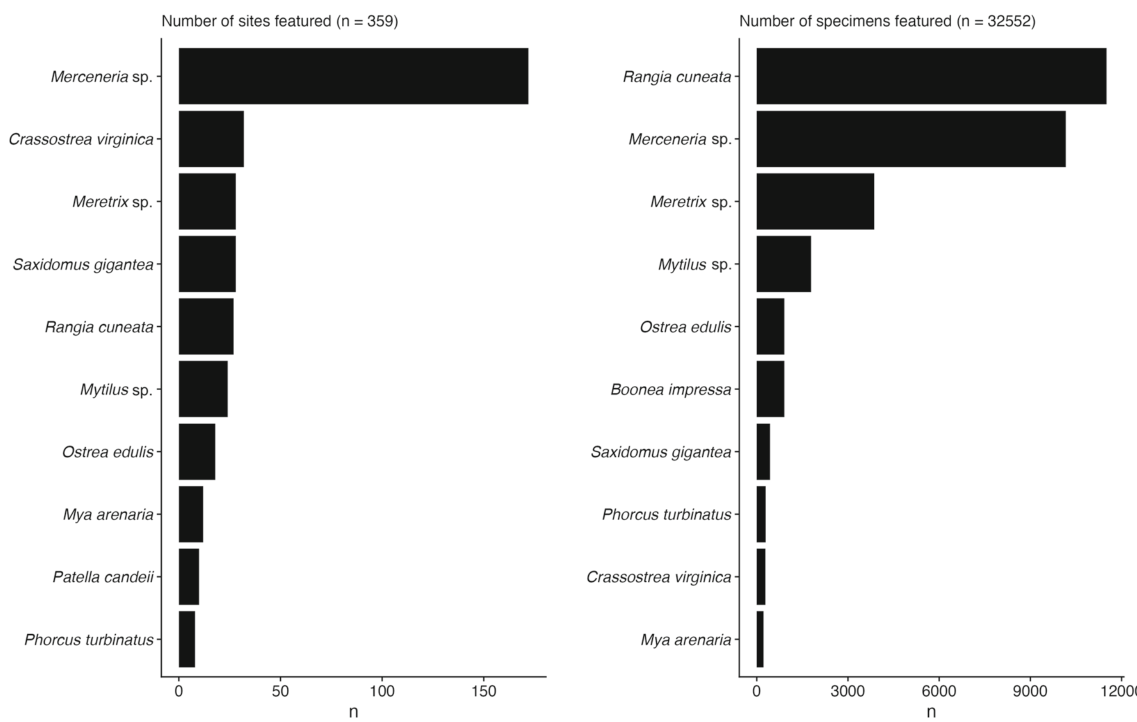


Fig. 5 Commonly used species *Left*: Shellfish species used by number of sites. *Right*: Shellfish species used by number of specimens. Not all species are shown, only the 10 most frequent ones

image since they are driven by single extensive seasonality surveys such as the one carried out on St. Catherine's Island (US-Georgia) with close to one hundred individual sites analysed (O'Brien and Thomas 2008).

The picture somewhat changes when looking at the number of specimens, where *Mercenaria* sp. still range very high (~10,000 in total) but *Rangia cuneata* are even more numerous (~11,500) due to the studies by Cheryl Claassen in the 1980s, where she studied the external patterns of over 3,000 specimens per site (Claassen 1986).

Excluding the specimens that were analysed using their external patterns, which are extremely accessible for seasonality analysis, *Rangia c.* drops to one study only using $\delta^{18}O$ by Blitz et al. (2014). *Merceneria* remains numerous (~9,600), closely followed by *Meretrix* and *Mytilus*. The high numbers of these three genera reflect the work of three archaeologists active in the 1980 and 1990s: Claassen, Quitmeyer, and Koike.

The majority of shells analysed were marine shells (34,448), with only a small fraction coming from freshwater (1804, 5%) and only one study trying itself on terrestrial snails, which did not provide a sample quantity (Gorman 1971). All freshwater shells come from work reported by Claassen in the 1980s and 1990s. That is not to say that no others exist or have been studied. Rather that there are significant gaps in our understanding of riverine seasonality, and that greater investment should be dedicated to these environments in the future.

Seasons

It seems at the same time obvious as well as overly simplistic to summarise the seasons of death for the entire dataset. Obvious because it might show some underlying pattern that is common to all sites, overly simplistic, because the sites are spread across the globe and have very little in common apart from being at the shores of water bodies.

Nevertheless, the study of all sites sites (n = 316, Fig. 6) that provided information in a way that was comparable across hemispheres (i.e. allocating months to hemispherical seasons depending on location but excluding local wet/dry seasons), showed that spring was the most common season to collect shellfish (spring: 331, summer: 260, autumn: 234, winter: 266). This seems to feed well into the theory that molluscs are only a food source that is used as a means to fill the hungry gap between new plant/fruit growth and lack of stored plant foods, which it can do very well. Indeed, spring and spring/winter or spring/summer results are very common across the dataset. But at the same time we can see that shellfish is eaten throughout the year and in fact, the most common combination of seasons is the year-round use of shellfish. This more general and frequent use underlines the importance of shellfish as a main staple in these communities and not only a resort to fill the hungry gap.

Lastly, since most studies are concentrated on Northern Europe and North America, there is an inherent bias against cases with other environmental conditions and seasonal setup. So that this statistic should rather reflect the general makeup of the field rather than how shellfish are typically collected throughout the year.

Site characteristics

I tried to be non-discriminatory regarding what kind of sites were being analysed. As such, there is a mix of site-contexts. By looking into the composition of this mix, I was hoping to find out more about "typical" shellfish seasonality sites and see whether there might be trends developing or gaps to address. Most generally, I wanted to see whether there is a focus on middens and mounds or whether layers of shells are equally interesting for researchers. Of the 418 sites, 217 (52%) were indeed middens and only 30 (7%) were layers, the remaining sites had no clear information.

In terms of coverage of these accumulations, layers were almost always studied across their entire stratigraphy (that is spits or sublayers), while the information for middens is less available. Only 33 sites report information in this regard and 21 of those covered all stratigraphic layers. There is a definitive trend towards the use of stable oxygen isotope analysis, the fewer layers of a midden were analysed, which reflects the trend in manageable sample numbers we saw in the comparison of methods earlier on site-level: Fewer shells in total cannot stretch as far.

Sedentism and general subsistence

Without going into the details of each site, which are more nuanced than what I show here, I looked into whether the occupants were generally sedentary or not and whether they were hunter-fisher-gatherers or not. What I hoped to find was whether seasonality studies are mostly restricted to non-sedentary hunter-fisher-gatherers and questions of their seasonal mobility or whether there is significant scope for the study of seasonality of e.g. sedentary farmers.

In my dataset, the majority (~60%) of sites did not have specific information about their hunter-fisher-gatherer or sedentism status. Of the 165 that have this information, 110 sites were indeed hunter-fisher-gatherer sites, with 28 of those being sedentary and 75 non-sedentary (the remaining were unclear about sedentism). Of the 27 sites not identified as hunter-fisher-gatherers, 26 were also sedentary sites. Additionally, there are 7 sites identified as sedentary without information on their subsistence.

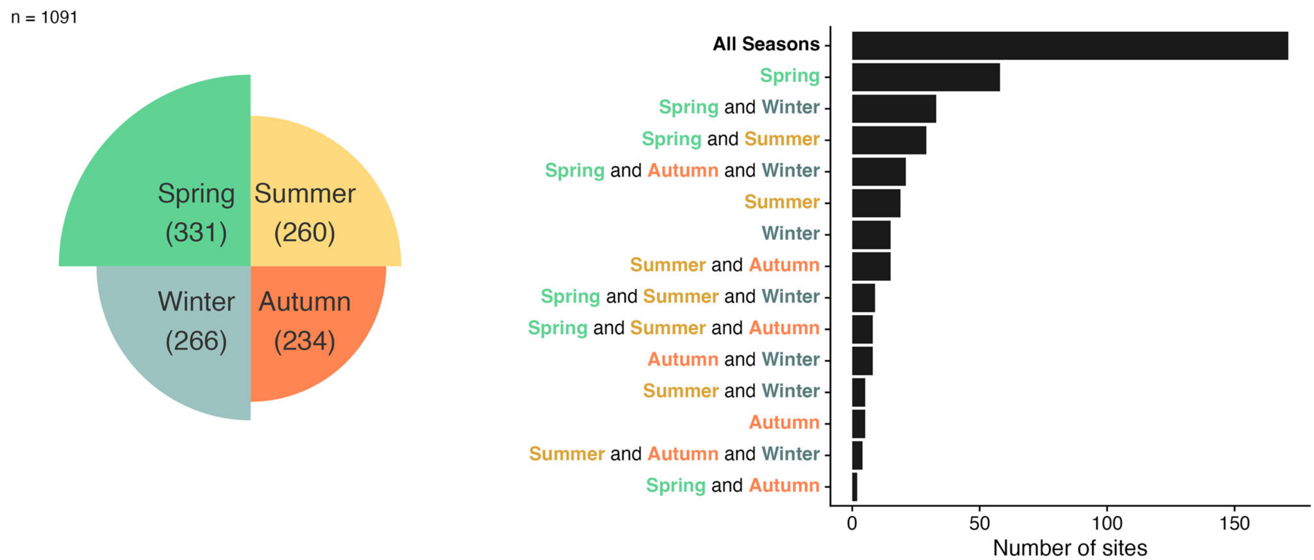


Fig. 6 **Simplified seasonal distribution** *Left*: All comparable seasonal data. Sites that have year-round occupation count towards all seasons. *Right*: Most common seasonal combinations

The sites of sedentary hunter-fisher-gatherers were found across the world (e.g. Japan, Denmark, the US, Australia) and were not restricted to one specific area or group of people, they also cover a range of time periods from the early Holocene to the last few centuries. One aspect they share however is that the majority was studied in the last 25 years with only 3 studies (Drover 1974; Monks 1977; Ham 1982) mentioning sedentary hunter-fisher-gatherers before then. Given the increase of research that has happened since the 2000s pointing more confidently towards complex coastal communities that live sustainably in one area and use marine resources in a way similar to harvesting domesticated crops (Rick 2023), I am inclined to say that the study of seasonality in these sedentary groups is becoming less about their mobility but rather changes in resource use across the year (Sanger et al. 2020).

Looking at the most commonly used seasons for sites of hunter-fisher-gatherers (or not) and sedentary or non-sedentary groups, the pattern of seasonal use stays similar to the overall distribution with year-round use of shellfish being the most frequent result for all cases.

Time periods

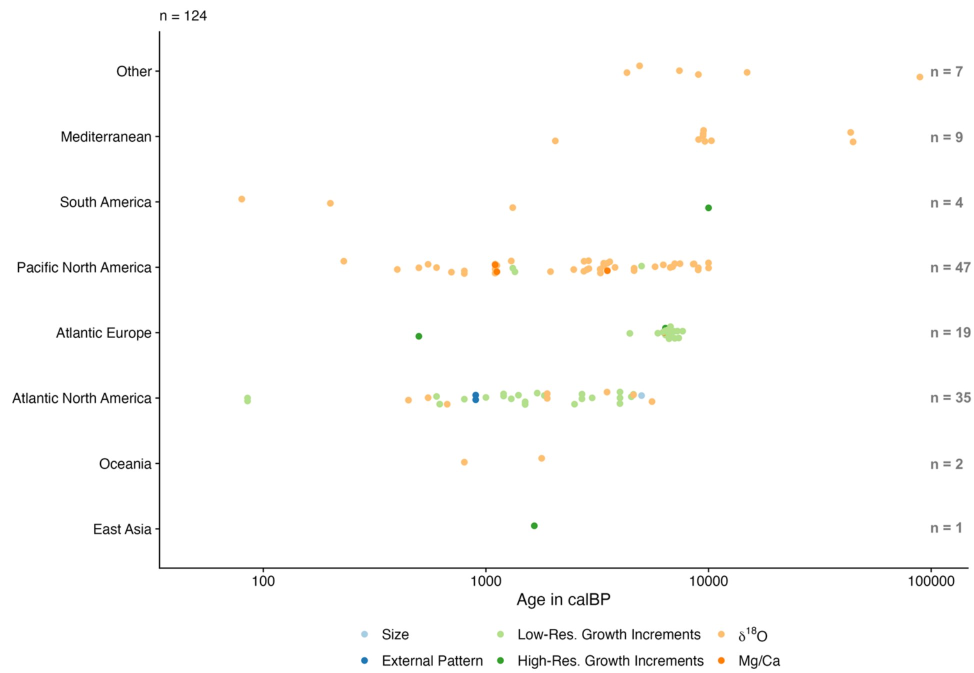
To see whether there are patterns in the time periods analysed, I have restricted myself to studies that provided calibrated radiocarbon dates (n = 124), because the temporal range of certain periods (e.g. Neolithic) differs between places. Most of those sites plot into the Holocene, which is not too surprising given that the study is of coastal sites and much of human prehistory along shorelines is currently underwater (Fig. 7).

The only method that really ventures into the Palaeolithic is stable oxygen isotope analysis, which is not surprising since it also works as a palaeoclimate proxy and is able to answer questions regarding the environmental context. In addition, these sites are more often cave sites and restricted in the number of samples available, so that a large percentage of preserved shell specimens can be studied while still being a manageable number of shells for isotope analysis.

Managing costs of stable oxygen isotope analyses

For the sites that were analysed using stable oxygen isotope samples, I have recorded the number of studied specimens as well as the average number of edge samples that were taken from each shell, to calculate the total number of isotope values, which was not always reported (Fig. 8). Edge samples are sequential samples that were taken from the shell edge, the location of the most recent increments, towards the less recent increments of the shell, usually covering the last few months or years of shell growth and recorded temperature, depending on the growth rate of the species or specimen as well as its age. Using this value, I wanted to gauge how the different studies compromised between a robust assessment of the season of collection and a robust assessment of the seasons within the shell assemblage. The former has a large number of edge samples (30+), the latter has a large number of shell specimens (50+). Trying to have large numbers of both quickly leads to very high research costs (+altwest2018molluscs) (e.g. with 10–15 \$ or € per sample and 30 samples for 50 specimens each results in 15,000 to 22,500 \$/€).

Fig. 7 Chronological overview of dataset by region and method



The increase of total isotope samples is very clear and linked to increased accessibility of such facilities. A roof that limits most studies seems to have established itself at around 600 samples per study (Fig. 8). How these samples are then distributed depends on the researcher. A lot of studies work simply with edge values, following a 1:1 trajectory and similar trajectories are apparent with most studies having more than 100 isotope values in total also using 10 edge samples or more, which for most mollusc species is enough to determine the season of death if there is a good understanding of the annual temperature range. In fact, many studies sample a few specimens using longer sequences to establish just that.

Two studies reach very high numbers of total stable oxygen isotope samples (both ~1300) (Burchell et al. 2013; García-Escárzaga et al. 2019). They work on two different species (*Saxidomus gigantea* and *Phorcus turbinatus*) with the first being longer lived than the second and being able to provide longer sequences of stable oxygen isotope val-

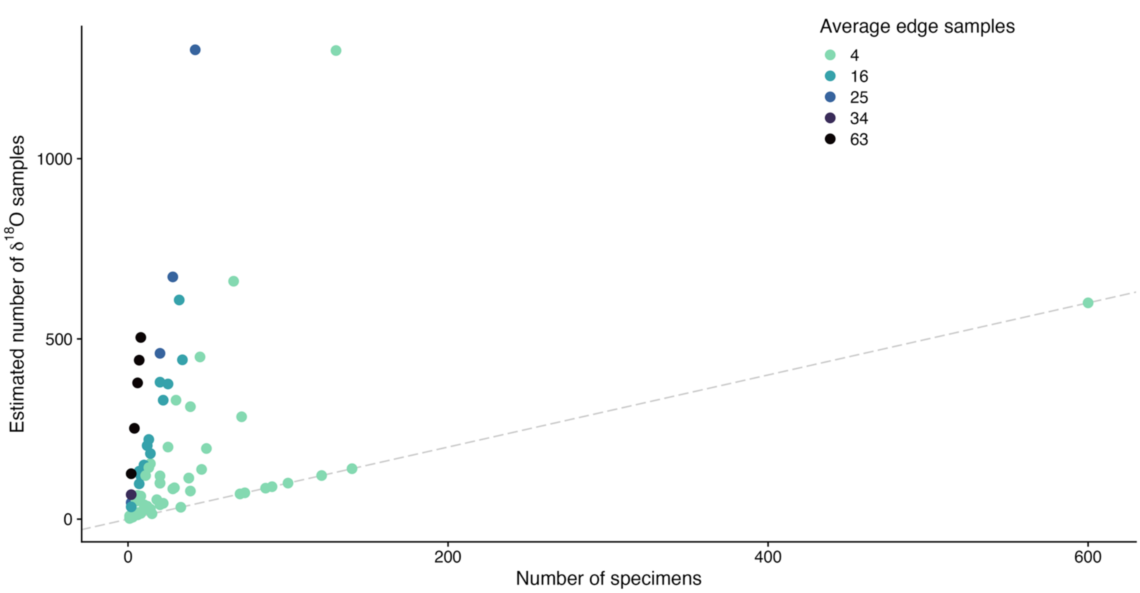


Fig. 8 **Number of stable oxygen isotope samples analysed** Total number of stable oxygen isotope samples compared to number of analysed specimens with the dotted line indicating a 1:1 relation of sample to specimen. The point colours indicate the number of edge samples divided into five groups

ues. In fact, top shells like *Phorcus turbinatus* have in other instances been sampled using 3 edge samples only, which arguably is not enough for a confident seasonal assessment (West et al. 2018).

Spotlighting past seasonality studies

Summarising previous research does not only mean counting of certain arbitrary parameters, but also understanding past goals and research perspectives. In the following I have selected a few studies from the past that contain such helpful perspectives and approaches, which have been somewhat lost on the way and I think are worth bringing up again. Ideas to follow down the rabbit hole for or arguments that need testing or rigorous application.

Context-specific seasonality

The first study is actually multiple studies that were at the time and are still sometimes credited internationally but did not shape the field in a way that I think it should have. These are the studies by Hiroko Koike from the 1970s and 1980s (Koike 1979, 1980). Koike started her research career in the growing field of sclerochronology, which she applied to the seasonality of shell middens as well as dwelling sites across a long period of Japanese history and prehistory. She then combined this approach with the study of animal biomass to better understand the use of marine and terrestrial animals and the impact people had on animal populations. She later on developed this into a study of the resource management systems of different societies.

At the beginning of her career, Koike started a thorough analysis of growth rates and growth structures of common Japanese clams and this work is mostly known as Koike (1973) "*Daily growth lines of the clam*, Meretrix Zusoria *- A basic study for the estimation of prehistoric seasonal gathering*" and (Koike 1979) "*Seasonal dating and the valve-pairing technique in shell-midden analysis*". But in addition there is also the larger publication (Koike 1980) "*Seasonal Dating by Growth-Line counting of the clam,* Meretrix Lusora", which includes a long list of individual seasonality studies of various contexts. Their setting in a variety of sites and contexts and the application of seasonality to them in a way that goes beyond the simple site-level seasonality that we see today is remarkable, particularly for the time, as the stratigraphic coverage of sites and the individual information for shells far exceeds some of today's studies. Among Koike's work is the Natsumidai site, also referenced in Koike (1979), where she developed the quantification of accumulation rates based on the 3D location of shells and their individual season of death. As far as I am aware, this has not been done since then. Comparable studies are 2D or 1D only (i.e. using the location on stratigraphic drawings or within a stratigraphic sequence, respectively) (Thompson and Andrus 2011; Hausmann and Meredith-Williams 2017) and sadly omit referring to Koike's previous work happening almost 40 years before and at a much better resolution.

The benefit of using shells as high-resolution stratigraphic tools to determine how shells accumulated and to provide a short-term context of accumulation to other remains and artefacts within, is a wholly underused aspect of this sample type and has not been picked up in earnest since Koike's work. One main reason today are the small quantities of shell specimens that can be analysed per site or per layer using stable oxygen isotopes. For context: of the 4,382 shell specimens at the site Koike determined the season of death for 644 (∼15%) of them. Most middens contain millions of shells and 15% would easily take a lifetime to analyse, but individual layers of interest or smaller piles of shell, as was the case in Natsumidai, should present potential candidates for similar analyses. Koike used growth increment analysis, which is able to study more shells without the significant investment of time and money, but some geochemical studies show similar promise (Finstad et al. 2013; Hausmann et al. 2023; Martínez-Minchero et al. 2023).

Studying shell deposits in the context of houses and dwellings present interesting scenarios in which the processing of shells could provide a more site-specific and personal context. Particularly including artefacts found within the layer and how they were discarded over the period of a few seasons (the accumulation at Natsumidai was estimated to have occurred over ∼500 days) could allow archaeologists to reveal importants insights into these short-term activities. Critically, the necessary stratigraphic information needs to be recorded during excavations with samples collected individually from the deposit rather than taken from bulk samples.

Growth incremental studies of the US

The other study I wanted to highlight is a piece by Cheryl Claassen (1990), a reply to a study by Lightfoot and Cerrato (1989) where she summarises the different approaches to seasonality studies in the US at the time, their background and the respective problems.

The reason why I wanted to highlight this study is that it summarises the way that many sites were studied during the 20th century in the US and points towards major problems with their interpretation. At the same time, the sheer amount of studies that happened at the time in this part of the world is astonishing and something that I think many seasonality researchers outside the US are not aware of.

At that point in shell seasonality research, archaeologists were mainly relying on growth incremental analyses of the internal structure of shells, a method that is not as common today due to the specimen specific variabilities in growth rate and shell structure. Back then, this variability was also known but addressed differently. Today we would rely on geochemical information to contextualise growth patterns (Gutiérrez-Zugasti et al. 2017) or measure the individual increment widths to relate them to tidal changes that provide additional information (Hallmann et al. 2009). The solution back then was to **a)** ignore the specimen to specimen variability and **live with the inaccuracies** (hence Claassen's reply), **b) quantify the inaccuracies** and apply an error (i.e. ± 2 months or more) to each specimen's determined season of death (also criticised by Claassen), or **c) study shells as one group** and assess how its seasonal make-up as a whole changes throughout the year. Solution **c** is Claassen's proposed method, since in hers and other studies of modern populations, the mollusc-to-mollusc variability in growth patterns is so strong, that the most reliable way of assessing what season they represent, is to group them and relate them to the typical growth-pattern mix of a specific month or season (Claassen 1988). For instance, during an actual winter month one might find shells with growth patterns indicating anything between early autumn and late winter. One individual shell will only tell you one point in time, which cannot fully be trusted given the variety of seasons found in winter, but a group of shells can characterise the specific month by its percentage of autumn and winter shells, which can be more reliable compared to the modern references. She also points out that comprehensive modern reference studies are often not carried out to prepare studies for solutions **a** and **b**, because it would show that the outcomes of the initial growth-study are inaccurate and do not capture the whole natural variability (over e.g. multiple years). Knowing how variable shell growth patterns can be, it is easy to agree with her solution **c** over **a** and **b**, as she writes somewhat dramatically:

> *To simply bracket each shell's count with an error margin* [...] *or an interpretation with a three-month margin, or a one-season margin is not sufficient for the task at hand, that of determining when this resource was harvested. The result of such a modification is to render the results useless.* (Claassen (1990), p. 83)

She uses the example of Kidder Point where shells have growth line patterns of "spring" and "summer", which were interpreted via solution **a** and **b** as a site being occupied in spring and summer. Claassen points out, that when interpreting these shells as one group that died at the same time, they reflect the modern composition of shells found in April and May (i.e. spring only). So by applying solution **c** Claassen reduces the error margin from spring to summer to spring only, improving the seasonal resolution of the analysis.

Alas, Claassen admits, and we now know — based on geochemical seasonality methods — that in most cases archaeological shells occur as seasonally mixed assemblage and selecting only specimens that were deposited at the same time is "*a criterion, which often cannot be met in excavation*" (Claassen 1988, p. 54). This issue can be due to how they accumulate or due to post-depositional movement, or because how we excavate the material (Hausmann and Meredith-Williams 2017). Grouping a mix of these shells as a single deposition, would brush over the variability in seasons and provide an average result only. So solution **c** does not sound viable either.

What to make of this dispute then, if from the current perspective all sides are wrong? Does this mean that all seasonality studies of growth incremental data should be disregarded? Certainly an attempt to reanalyse the method needed to be done. One example is by Quitmyer et al. (1997), who link growth incremental data with stable oxygen isotopes and carry out comparative modern reference studies along the southern Atlantic coast of the US involving more than 2,000 specimens with as many as 1,100 per site. Across this dataset they did find common trends but also acknowledge the variability within even one locality, the invisibility of assigning the wrong growth stage, the year-to-year variability, the similarity of seasons (e.g. months of June to October looking identical), and the problem of some growth stages (i.e. light and dark bands) occurring across the entire year.

While this study does not invoke a tremendous amount of confidence in projecting modern seasonal patterns into the past and use them for the analysis of archaeological shells, it provides a) the limits of a method that can be helpful for answering very specific questions, and b) a measurable amount of spatial and temporal variability that can be applied to existing datasets. Future studies might well look to Quitmeyer et al. (1997) to tackle other growth incremental studies that need re-assessment. Indeed, Claassen (1990) points out that many other interpretations are in need of re-assessment because they are based on growth incremental studies that are too short or too small in time and space.

The main point I would like to make here is that this very active period of seasonality research, which had an immense spatial density of analysed sites, was accompanied by some major disagreements on the fundamental aspects of shell seasonality. It also shows that even after one modern study has been carried out, it is well worth doing more, because you may have different outcomes. Even in geochemical studies there are many unknowns, as the temperature records are only as good as the shell growth rate is predictable (Schöne 2008a). In stable oxygen isotope sequences, the occasional summer or winter hiatus is overlooked because it is too difficult to assess unless regular. Seemingly objective assessments of seasons by splitting the year into quarters of isotope ranges, overlook that in some areas water stays cold well into late spring (Kwiecien et al. 2022). Limpet species seem to have locality specific fractionation processes that cannot only be explained by the locality-specific water chemistry and are currently simply ignored in terms of how stable they were through archaeological time (e.g. offsets found by Fenger et al. 2007: +1.01‰; Ferguson et al. 2011: +0.72‰; Gutiérrez-Zugasti et al. 2017: +0.36‰; Parker et al. 2017: +1.3‰; Prendergast and Schöne 2017: -0.72‰). Temperature data that modern shells are compared to and that provide the necessary reference (together with water chemistry) to assess the predictable fractionation of stable oxygen isotope values in shells, are more and more often taken from satellite data, rather than local temperature loggers, because these would need to be positioned at least one year prior to shellfish collection. Satellite and local temperature data, can and does differ (Hausmann et al. 2017), introducing an error-source that can be used to explain away a lot of other potentially systemic issues in reconstructing sea surface temperatures and the season of death. Lastly, elemental data (Mg/Ca) has more than once provided contrasting results about whether they are internally or externally controlled (Vihtakari et al. 2017) and even with new mapping systems being developed, no general rule can yet be found (Hausmann et al. 2023). While on their own, these issues are likely not problematic, but ignoring them can develop into a false sense of security where, because it has worked before, research might become less rigorous and extensive as they might require to be. Modern studies are at the core of reconstructing seasonality in the past. Without them it is a guessing game that archaeologists cannot afford to rely on.

Future questions and outlook

Having looked back not necessarily at the most recent developments in shellfish seasonality, but at the overall makeup of studies over the last 50 years with some detailed looks at specific studies, it is apparent that the field is far from rigid. It does not necessarily follow technical developments but rather lives from the time and effort that people find to invest into it. One seasonality study is often not enough and the more places we start to look, the more variability is revealed. This is the case for modern reference studies, showing that there is a limit to how well we understand shell growth, and also for archaeological studies, where either multi-site studies or studies with high stratigraphic resolution reveal that no one seasonal pattern usually exists. On the other hand, there are numerous coastlines of the world, where shell middens are preserved, but no seasonality studies have been carried out at all (Robson et al. 2024). Numbers for the global South are particularly low, which can be explained as a reflection of the lacking accessibility of the research methods required to carry out seasonality studies. The development of local laboratories that can carry out this research more easily should be fostered.

This dynamic leaves us much potential to work with in the future and when doing so there should be no shame in picking up on thoughts and ideas from the early beginnings of seasonality research. These studies were still experimenting and working outside a normative thinking about shell midden seasonality. For example, Shackleton (1973) mused that the tidal influence on the stable oxygen isotope values should be checked and tested this in his study of *Patella tabularis* using *Perna perna* shells as a low-tide baseline. This idea was recently picked up again by Jazwa et al. (2020). They did indeed find that a vertical difference of 1 m can change temperature estimates by 1.8°C (± 0.42‰) and thus expand error margins for species that are found at a range of tidal depths. Koike's (1979) high-resolution stratigraphic approach from the early beginnings of shell seasonality research was picked up again after a long break, even though not acknowledged and ignorant of it Thompson and Andrus (2011); Hausmann and Meredith-Williams (2017). The core idea remained the same and efforts should be renewed to aim for studies that define positions and seasons for all shell specimens in one context.

Experimenting in other areas also has lots of potential. The rudimentary statistical summary I carried out here showed a lack of studies engaging with shells along rivers. While not as numerous, these sites exist and likely operated entirely differently than coastal sites. They will require rigorous modern studies, for which archaeologists cannot solely rely on colleagues in the geosciences, who are usually less interested in determining the season of capture or in researching a species that does not play as much of a role as food source today as it did in the past.

The problems with many modern studies (including my own) which I outlined above also show that coastal sites would benefit from an improved understanding of how their shells operate on a seasonal basis. The main problem is that the investment of time into reference studies is immense with many studies having to start a year or more in advance, which is not in agreement with short-term research positions many scholars have today. The multi-year, multi-locality, multi-species studies sought after by Claassen (1990) are far beyond what many archaeologists can achieve, particularly because no archaeological data will be produced while one waits until the shells have grown. Furthermore, local temperature loggers are usually expensive, not always possible to deposit, and are occasionally stolen. If one wanted to improve the field, tackling these technical and sometimes administrative problems could well be a point to focus on.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12520-024-02056-8.

Acknowledgements Thanks to Harry Robson, who suggested looking into this dataset in the first place, and to Asier García-Escárzaga for inviting me to contribute to this special issue. I also have to thank two anonymous reviewers, who added important insights and improved the manuscript as a whole. Any mistakes are of course mine.

Author Contributions NH carried out data collection, the data analysis, and wrote the manuscript.

Funding NH acknowledges funding by the German Research Foundation (DFG) Project number 439799406

Availability of Data and Material/ Data Availability All data are available within the repositories mentioned in the main text https://github.com/Niklas-palaeo/Shell-Seasonality-Review.

Code Availibility All code is available within the repositories mentioned in the main text.

Declarations

Competing Interests The authors declare no competing interests.

Ethics Approval Not applicable

Consent to Participate Not applicable

Consent for Publication Not applicable

References

Allen M, Payne B (2017) Molluscs in archaeology: an introduction. Molluscs in archeology: methods, approaches and 1–4

Blitz JH, Andrus CFT, Downs LE (2014) Sclerochronological measures of seasonality at a late woodland mound on the mississippi gulf coast. Am Antiq 79(4):697–711

Burchell M, Hallmann N, Martindale A, Cannon A, Schöne BR (2013) Seasonality and intensity of shellfish harvesting on the north coast of British Columbia. J Island Coastal Archaeol 8(2):152–169

Claassen C (1986) Shellfishing seasons in the prehistoric southeastern united states. Am Antiq 51(1):21–37

Claassen C (1988) Techniques and controls for the determination of seasonality in shellfishing activities. Recent Develop Environment Anal Old New World Archaeol 416:51

Claassen C (1990) The shell seasonality technique in the eastern united states: a reply to lightfoot and cerrato. Archaeol Eastern North Am 18:75–87

Coutts P, Higham C (1971) The seasonal factor in prehistoric New Zealand. World Archaeol 2(3):266–277

Drover CE (1974) Seasonal exploitation of chione clams on the Southern California Coast. J California Anthropol 1(2):224–232

Emiliani C, Cardini L, Mayeda T (1964) Paleotemperature analysis of fossil shells of marine mollusks (food refuse) from the Arene Candide Cave, Italy and The Haua Fteah Cave, Cyrenaica. Isotopic cosmic chemistry (pp 133–156). pascal-francis.inist.fr

Fenger T, Surge D, Schöne BR, Milner N (2007) Sclerochronology and geochemical variation in limpet shells (Patella vulgata): a new archive to reconstruct coastal sea surface temperature. Geochem Geophys Geosyst 8(7):Q07001

Ferguson JE, Henderson GM, Fa DA, Finlayson JC, Charnley NR (2011) Increased seasonality in the Western Mediterranean during the last glacial from limpet shell geochemistry. Earth Planet Sci Lett 308(3–4):325–333

Finstad KM, Ingram BL, Schweikhardt P, Lightfoot KG, Luby EM, Coles GR (2013) New insights about the construction and use of shell mounds from the geochemical analysis of mollusks: an example from the greater san francisco bay. J Archaeol Sci 40(6):2648–2658

García-Escárzaga A, Gutiérrez-Zugasti I, Cobo A, Cuenca-Solana D, Martín-Chivelet J, Roberts P, GonzÁlez-Morales MR (2019) Stable oxygen isotope analysis of phorcus lineatus (Da Costa, 1778) as a proxy for foraging seasonality during the mesolithic in Northern Iberia. Archaeological Anthropological Sci 11:5631–5644

Gorman C (1971) The hoabinhian and after: subsistence patterns in Southeast Asia during the late pleistocene and early recent periods. World Archaeol 2(3):300–320

Gutiérrez-Zugasti I, SuÁrez-Revilla R, Clarke LJ, Schöne BR, Bailey GN, GonzÁlez-Morales MR (2017) Shell oxygen isotope values and sclerochronology of the limpet patella vulgata linnaeus 1758 from northern iberia: implications for the reconstruction of past seawater temperatures. Palaeogeogr Palaeoclimatol Palaeoecol 475:162–175

Hallmann N, Burchell M, Schöne BR, Irvine GV, Maxwell D (2009) High-resolution sclerochronological analysis of the bivalve mollusk Saxidomus Gigantea from Alaska and British Columbia: techniques for revealing environmental archives and archaeological seasonality. J Archaeol Sci 36(10):2353–2364

Ham L (1982) Seasonality, shell midden layers, and coast salish subsistence activities at the crescent beach site, DgRr 1 PhD thesis

Hausmann N (2024) Data and code for "a current assessment and commentary on the field of shell seasonality." https://doi.org/10.17605/OSF.IO/BJV3W

Hausmann N, Meredith-Williams M (2017) Exploring accumulation rates of shell deposits through seasonality data. J Archaeological Method Theory 24(3):776–795

Hausmann N, Robson HK, Hunt C (2019) Annual growth patterns and interspecimen variability in Mg/Ca records of archaeological Ostrea edulis (european oyster) from the late Mesolithic Site of Conors Island. Open Quaternary, 18

Hausmann N, Theodoraki D, Piñon V, Siozos P, Lemonis A, Anglos D (2023) Applying laser induced breakdown spectroscopy (LIBS) and elemental imaging on marine shells for archaeological and environmental research. Sci Rep 13(1):19812

Jazwa CS, Wolfe CA, Chu EY, Stull KE (2020) The effects of vertical position in the intertidal zone on the δ^{18}O and δ^{13}C composition of Mytilus californianus shell carbonate. J Archaeological Sci: Reports 34:102587

Keene DA (2012) Reevaluating the use of impressed odostome (boonea impressa) as a Season-of-Capture indicator for oysters. T. Reitz EJ Quitmyer IR (Ed.), Seasonality and human mobility along the georgia bight. (pp 165–170). New York: American Museum of Natural History

Koike H (1973) Daily growth lines of the clam. Meretrix lusoria. Anthropol Sci 81(2):122–138

Koike H (1979) Seasonal dating and the valve-pairing technique in shell-midden analysis. J Archaeol Sci 6(1):63–74

Koike H (1980) Seasonal dating by growth-line counting of the clam, meretrix lusoria. University of Tokyo Press

Kwiecien O et al (2022) What we talk about when we talk about seasonality - a transdisciplinary review. Earth Sci Rev 225(103843):103843

Leng MJ, Lewis JP (2016) Oxygen isotopes in molluscan shell: applications in environmental archaeology. Environ Archaeol 21(3):295–306

Lightfoot KG, Cerrato RM (1989) Regional patterns of clam harvesting along the atlantic coast of North America. Archaeol Eastern North America 17:31–46

Mannino MA, Thomas (2023) Advances in the archaeological study of invertebrate animals and their products. Wiley

Martínez-Minchero M et al (2023) Comparison of Mg/Ca concentration series from patella depressa limpet shells using CF-LIBS and LA-ICP-MS. Talanta 251:123757
Milner N (2001) At the cutting edge: using thin sectioning to determine season of death of the European Oyster, Ostrea Edulis. J Archaeological Sci 28(8):861–873
Monks GG (1977) An examination of relationships between artifact classes and food resource remains at deep bay, dise 7. PhD thesis. University of British Columbia
Monks GG (1981) Seasonality studies. Advances Archaeological Method Theory 4:177–240
O'Brien M, Thomas (2008) The molluscan incremental sequence. Native American Landscapes of St. Catherines Island, Georgia: II. The Data, Anthropological Papers 88:475–497
Parker WG, Yanes Y, Surge D, Mesa-HernÁndez E (2017) Calibration of the oxygen isotope ratios of the gastropods patella candei crenata and phorcus atratus as high-resolution paleothermometers from the subtropical eastern atlantic ocean. Palaeogeogr Palaeoclimatol Palaeoecol 487(Supplement C), 251–259
Prendergast AL, Schöne BR (2017) Oxygen isotopes from limpet shells: implications for palaeothermometry and seasonal shellfish foraging studies in the mediterranean. Palaeogeogr Palaeoclimatol Palaeoecol 484:33–47
Prendergast AL, Stevens RE (2014) Molluscs (Isotopes): analyses in Environmental 689 Archaeology. en. In: Encyclopedia of global archaeology. Ed. by C. Smith. Springer New 690 York, pp 5010–5019
Quitmyer IR, Hale HS, Jones DS (1985) Paleoseasonality determination based on incremental shell growth in the hard clam, mercenaria mercenaria, and its implications for the analysis of three Southeast Georgia Coastal Shell Middens. Southeastern Archaeol 27–40
Quitmyer IR, Jones DS, Arnold WS (1997) The sclerochronology of hard clams, Mercenaria spp., from the south-eastern U.S.A.: a method of elucidating the zooarchaeological records of seasonal resource procurement and seasonality in prehistoric shell middens. J Archaeol Sci 24(9):825–840
Rick TC (2023) Shell midden archaeology: current trends and future directions. J Archaeological Res
Robson HK, Hausmann N, Milner N (2023) Shell middens. In: Encyclopedia of archaeology (pp 58–70)
Robson HK, Hausmann N, Milner N (2024) Shell middens. Encyclopedia of archaeology. Academic Press (pp 58–70)
Sanger MC, Quitmyer IR, Colaninno CE, Cannarozzi N, Ruhl DL (2020) Multiple-proxy seasonality indicators: an integrative approach to assess shell midden formations from late archaic shell rings in the Coastal Southeast North America. J Island Coastal Archaeol 15(3):333–363
Schöne BR (2008a) The curse of physiology–challenges and opportunities in the interpretation of geochemical data from mollusk shells. Geo-Mar Lett 28(5–6):269–285
Schöne BR (2008b) The curse of physiology–challenges and opportunities in the interpretation of geochemical data from mollusk shells. Geo-Marine Lett 28:269–285
Schweikhardt P, Ingram BL, Lightfoot K, Luby E (2011) Geochemical methods for inferring seasonal occupation of an estuarine shellmound: a case study from San Francisco bay. J Archaeol Sci 38(9):2301–2312
Shackleton NJ (1970) Marine mollusca in archaeology. Sci Archaeol: A Survey of Progress Res 407
Shackleton NJ (1973) Oxygen isotope analysis as a means of determining season of occupation of prehistoric midden sites. Archaeometry 15(1):133–141
Surge D, Lohmann KC, Dettman DL (2001) Controls on isotopic chemistry of the american oyster, Crassostrea virginica: implications for growth patterns. Palaeogeogr Palaeoclimatol Palaeoecol 172(3):283–296
Thomas KD (2015a) Molluscs emergent, part i: themes and trends in the scientific investigation of mollusc shells as resources for archaeological research. J Archaeol Sci 56:133–140
Thomas KD (2015b) Molluscs emergent, part II: themes and trends in the scientific investigation of molluscs and their shells as past human resources. J Archaeol Sci 56:159–167
Thompson VD, Andrus CFT (2011) Evaluating mobility, monumentality, and feasting at the sapelo island shell ring complex. Am Antiq 76(2):315–343
Twaddle RW, Ulm S, Hinton J, Wurster CM, Bird MI (2016) Sclerochronological analysis of archaeological mollusc assemblages: methods, applications and future prospects. Archaeol Anthropol Sci 8(2):359–379
Vihtakari M, Ambrose Jr WG, Renaud PE, Carroll ML, Berge J, Clarke LJ, Cottier F, Hop H (2017) A key to the past? element ratios as environmental proxies in two arctic bivalves. Palaeogeogr Palaeoclimatol Palaeoecol 465, Part B:316–332
Weide ML (1969) Seasonality of Pismo clam collecting at Ora-82. Tech rep 11. Los Angeles: 736 University of California Archaeological Survey Annual Report 11:127–141
West CF, Burchell M, Andrus CFT (2018) Molluscs and paleoenvironmental reconstruction in island and coastal settings: variability, seasonality, and sampling. Zooarchaeology in practice: Case studies in methodology and interpretation in archaeofaunal analysis, 191–208
Zimmt JB, Lockwood R, Andrus CFT, Herbert GS (2019) Sclerochronological basis for growth band counting: a reliable technique for life-span determination of Crassostrea virginica from the Mid-Atlantic United States. Palaeogeogr Palaeoclimatol Palaeoecol 516:54–63

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.