

## RESEARCH PAPER

# Catch Per Unit Research Effort: Sampling Intensity, Chronological Uncertainty, and the Onset of Marine Fish Consumption in Historic London

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As the cumulative volume of ecofactual data from archaeological sites mounts, the analytical tools required for its synthesis have not always kept pace. While recent attention has been devoted to spatial aspects of meta-analysis, the methodological challenges of chronological synthesis have been somewhat neglected. Nowhere is this issue more acute than for urban sites, where complex, well-dated stratigraphy; rich organic remains; and multiple small- to medium-scale excavations often lead to an abundance of small datasets with cross-cutting phasing and varied chronological resolution. Individually these may be of limited value, but together they can represent the environmental and socioeconomic history of a city. The challenge lies in developing tools for effective synthesis.

This paper demonstrates a new approach to chronological meta-analysis of ecofactual data, based upon (a) use of simulation to deal with dating uncertainty, and (b) calibration of results for variable research intensity. We apply this approach to a large body of historic-period fish bone data from London, revealing otherwise undetectable detail regarding one of the most profound shifts in medieval English economic and environmental history: the sudden onset of marine fishing commonly known as the Fish Event Horizon. Most importantly, we show that this phenomenon *predates* any visible decline in deposition of freshwater fish, and hence cannot have been driven by depletion of inland fisheries as has sometimes been suggested.

The R package developed for this research, *archSeries*, is freely available.

**Keywords:** zooarchaeology; meta-analysis; medieval fishing; environmental history; chronological uncertainty; urban archaeology; fish bones; aoristic analysis; Fish Event Horizon; sampling intensity

## Introduction

Recent decades have seen widespread recovery and analysis of a wide suite of ecofactual remains from archaeological sites, particularly in territories with systematic frameworks and guidance for development-led archaeology. As the cumulative volume of ecofactual data has mounted, however, the analytical tools required for its synthesis across space and time have not always kept pace. While recent attention has been devoted to spatial aspects of meta-analysis, particularly through increasingly sophisticated applications of GIS (see e.g. Livarda and Orengo 2015; McKechnie and Moss 2016), the methodological and statistical challenges of chronological synthesis have been somewhat neglected.

Nowhere is this issue more acute than for urban archaeological sites. A typical combination of complex, well-dated stratigraphy, rich organic remains, and multiple small- to

medium-scale excavations often leads to an abundance of small datasets with cross-cutting phasing and varied chronological resolution. Separately, many of these datasets are of limited value; together they can represent the environmental and socio-economic history of a city. The quality of excavation and documentation in this context is often very high, but the resources available for subsequent analysis beyond the level of individual projects are variable. There thus exists a rich and under-utilised archival resource for addressing some of the big questions of urban archaeology, and a need to develop analytical tools enabling optimal use of this resource.

In the medieval period of western Europe, one of those big questions is the extent to which long-range provisioning underpinned urban development and population growth. A key development in this context is the dramatic shift towards marine – and apparently away from freshwater – resources that occurred in England around the start of the 11th century AD, particularly at urban settlements. This ‘Fish Event Horizon’ marks a significant change in the resource bases of medieval towns, and represents the ultimate origin of modern commercial marine fisheries in the North Sea and beyond (Barrett et al. 2004a; 2004b).

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This paper discusses two major challenges in urban ecofactual synthesis: chronological uncertainty and variable research intensity. We review recent approaches to chronological synthesis, particularly aoristic analysis and Monte Carlo simulation, before demonstrating a method that allows results to be ‘calibrated’ for the intensity of research on different periods, and hence permits inferences regarding changes in *absolute* frequency of taxa in the archaeological record. This is applied to a large fish bone dataset from London in order to address two key questions relating to the Fish Event Horizon as manifested in the city: (a) how sudden was the shift towards marine fish; and (b) was it accompanied by an absolute rather than relative decrease in freshwater fish deposition?

Perhaps fittingly, our approach draws inspiration from a concept used in fisheries biology for more than a century (Garstang 1900) and more recently adopted into fisheries history (Poulsen and Holm 2007): catch per unit effort (CPUE). Where data exist for both the amount of fish caught and the distribution of fishing effort, researchers can use these to infer relative abundance of stocks over time. Our approach to the zooarchaeological record is analogous: where fisheries researchers assess changes in the number of fish in the sea, we infer fluctuations in the numbers of fish deposited, replacing fishing effort with archaeological sampling intensity and the yield of live fish with the ‘catch’ of archaeological fish bones.

### Background: the ‘Fish Event Horizon’

Having been rare since the onset of the Neolithic (c.4000 cal BC), marine fish taxa suddenly reappear in the English archaeological record in significant numbers from the start of the 11th century AD, often making up more than half of identified fish specimens in sieved assemblages from inland sites (Barrett et al. 2004a; 2004b). In the first instance this was primarily an urban phenomenon, with percentages at rural sites increasing more gradually over the following centuries. This resurgence of marine fish is starkest for cod (*Gadus morhua*), but related species such as haddock (*Melanogrammus aeglefinus*), saithe (*Pollachius virens*), ling (*Molva molva*), and hake (*Merluccius merluccius*) all became important by the 13th century. The phenomenon had some precursors at early medieval elite sites (Reynolds 2016) and in the form of herring at proto-urban trading centres, which from the seventh to eighth centuries onwards commonly contributed up to 20% of fish by NISP (fragment count) and occasionally more, for example at Castle Mall, Norwich, England (Locker 2009). Nonetheless, the abundance of herring also increased dramatically around AD 1000, reaching a median of 40–50% of fish NISP between the 11th and 16th centuries at both urban and rural sites.

Synthesis of fish bone data from Flanders, Belgium, reveals a broadly similar phenomenon (Ervynck et al. 2004), albeit with differences in the chronologies for specific taxa – flatfish playing a more important role while gadids remain rare until the 13th century (Van Neer and Ervynck 2016). Meanwhile, stable isotopic analysis of human bones from English sites (Müldner 2016) supports the idea of a substantial increase in marine protein from

around the 11th century, albeit with an earlier spike in marine signatures during the Roman period (Müldner 2013 c. AD 43–410) that is not clearly matched by the fishbone record (Locker 2007) and may to some extent represent shellfish consumption.

Various factors have been put forward as possible causes for the Fish Event Horizon. On the supply side, an initial hypothesis that the change was driven partly by long-range trade in dried cod – and perhaps other gadids – from Norway (Barrett et al. 2004a, 624–627) has now been disproven: cod consumed in London and elsewhere appear to have been primarily North Sea catches until at least the mid 13th century, based on stable isotopic composition and anatomical representation (Barrett et al. 2011; Orton et al. 2014; Harland et al. 2016). Climatic conditions can probably thus be ruled out: the same warming that might have been expected to increase cod productivity in northern waters would if anything have depressed it in the southern North Sea, as this area is towards the species’ southern limit (Barrett et al. 2004b, 2419–2420). Yet cod are one of the main species implicated in the Fish Event Horizon in England – although not, interestingly, in Flanders (Van Neer and Ervynck 2016).

On the demand side, population growth, urbanisation, and the development of market economies are likely to have played significant roles (Hoffmann 2001, 144; Barrett 2016, 265; Kowaleski 2016). The medieval period in England, as elsewhere in Europe, saw rapid population growth and development of urban settlements – although the precise scale and timing of these changes are notoriously hard to establish either from historical or archaeological sources (Dyer 2002; Langdon and Masschaele 2006; Astill 2009) – and it is specifically at early urban sites that the Fish Event Horizon first becomes apparent in the 11th century. Towns and cities represent concentrations of net consumers of food; as these concentrations grew the increasing demand must have been met by a combination of intensified production and expansion of hinterlands (Galloway and Murphy 1991; Hoffmann 2001; Barbier 2011). To the extent that transport and land availability placed high costs on expansion in the supply of terrestrial bulk goods, marine resources may have represented an attractive alternative food source (Hoffmann 2002).

Demand for fish will also have been influenced by cultural factors. In particular, Christian fasting practices are likely to have played a role, potentially prohibiting consumption of most meat for much of the year and making fish an attractive alternative for those with access to it (Hoffmann 2001, 141). Aelfric’s letters to Wulfstan (c.AD 1005–1010) noted clergy could fish but not hunt or hawk, although this is not explicitly tied to fasting. The early development and enforcement of fasting rules in England is complex and incompletely understood, however, especially for the secular community (see Barrett et al. 2004a, 629–630; Serjeantson and Woolgar 2006, 104).

Finally, the onset of sea fishing might have been stimulated in part by depletion of freshwater resources due to overfishing and/or habitat destruction (Hoffmann 2001, 144; Barrett et al 2004a, 628; Barrett 2016; Roberts 2007).

Apart from significant exploitation of freshwater taxa, the late first and early second millennia also saw several developments likely to have reduced productivity of freshwater ecosystems across much of Europe: widespread construction of mill dams (Lenders et al. 2016), intensification of agriculture, and increased nutrient loads due to growing populations of people and of domestic animals (Hoffmann 1996; Hoffmann 2004, 24; see also Häberle et al. 2016a; 2016b; Van Neer and Ervynck 2010, 2–3). In this scenario the shift to coastal and offshore waters could be seen as a response to diminishing returns from rivers and lakes. Alternatively, demand may simply have outstripped freshwater fisheries' supply (Hoffmann 2002; Galik et al. 2015; Kowaleski 2016).

In attempting to evaluate the latter hypotheses we encounter a classic limitation of zooarchaeological research, namely that specimen counts are, in normal circumstances, closed datasets: if the percentage frequency of one category increases that of others must necessarily decrease. This can only be circumvented where some external control can be brought to bear, for example the volume of sediment from which specimens were recovered. As such, the relative decrease in freshwater remains observed at the Fish Event Horizon is an inevitable corollary of the increase in marine specimens, and may or may not reflect any absolute decline in their consumption.

In order better to understand the roles of these various processes in the Fish Event Horizon, it is thus necessary to ascertain whether the apparent decline in freshwater fish is real or simply an artefact of increasing marine fish consumption, and to refine the chronology for both apparent trends. If a decline in freshwater fish remains can be shown to start *before* the increase in marine species, this would support the hypothesis that overfishing and/or pollution of rivers and lakes began in the early medieval period and contributed to the move to marine fishing. Conversely if no such decline can be shown, or if it *post*-dates the Fish Event Horizon, this would suggest that the development of marine fisheries was driven primarily by increased overall demand for fish and/or changes in culinary tastes.

### Approaches to chronological synthesis

Given the centrality of chronology to archaeology, there has been surprisingly little debate on how the inevitable uncertainty in the dating of individual archaeological entities – be they sites, stratigraphic units, artefacts, or ecofacts – can be built into meta-analyses and syntheses (Crema 2012, 441; see also Bevan et al. 2013; Baxter and Cool 2016). Research based directly upon radiocarbon databases is somewhat ahead of the wider discipline here: increasingly sophisticated and extensive studies have synthesised  $^{14}\text{C}$  results across large numbers of sites, employing Monte Carlo methods (i.e. modelling of complex situations via repeated random sampling) and testing the resulting distributions rigorously against null models (e.g. Shennan et al. 2013; Timpson et al. 2014; Crema et al. 2016, Porčić et al. 2016). In these cases it is the dates themselves that are used as proxies for human activity rather than the archaeological entities that they represent, but the principles underlying such studies

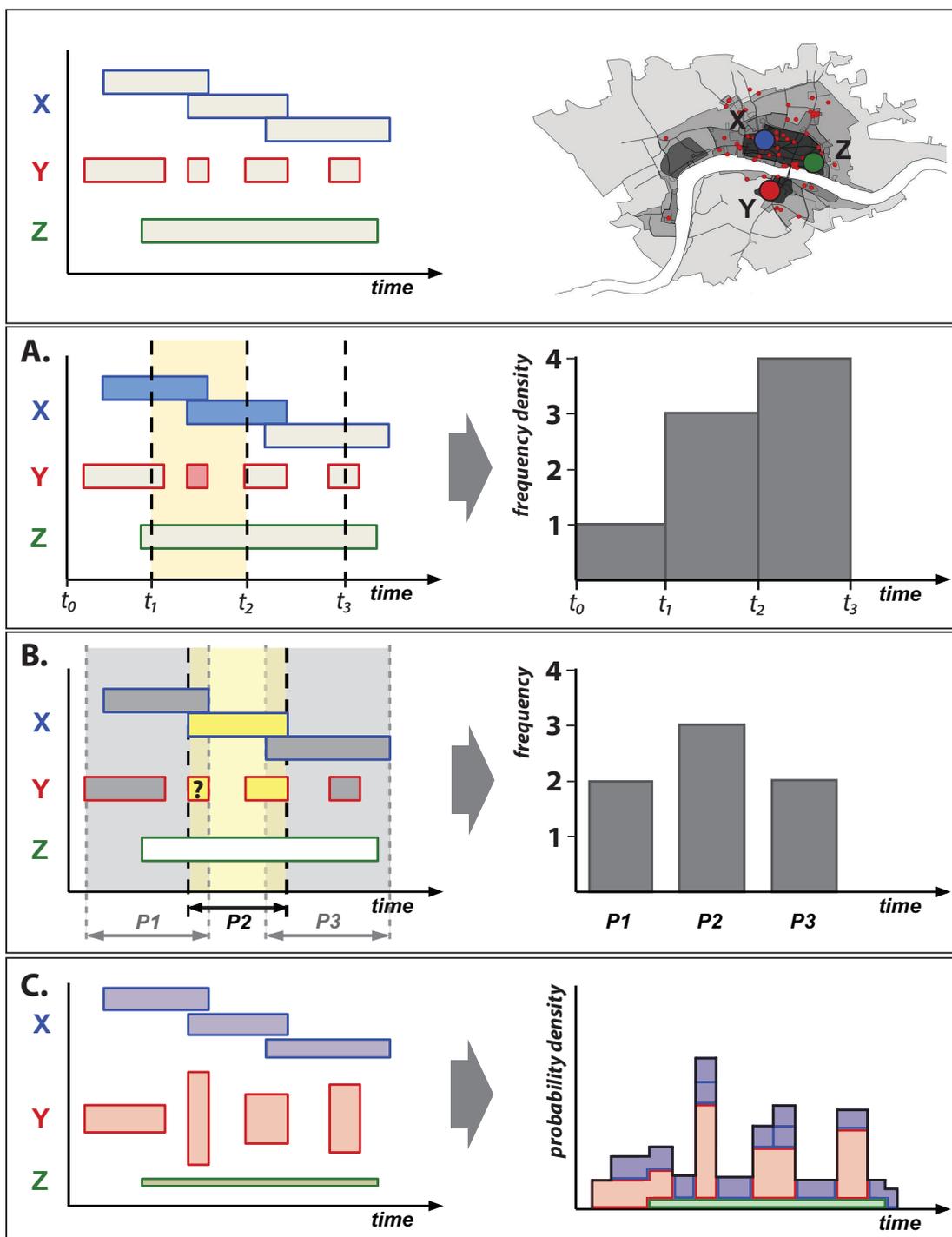
have rarely been applied to other forms of archaeological dating – including the combination of artefactual, historical, and dendrochronological information typically employed at medieval urban sites. Crema's (2012; see also Crema et al. 2010) study of the chronological distribution of Jomon pit houses is a worthy exception, providing the inspiration for the approach adopted here (see also Baxter and Cool 2016; or Edinborough et al. 2015 for a rather different example).

Conventional approaches to grouping variably dated material have often focused on the mid-points of date ranges assigned to individual entities, using these to place entities into chronological categories of – typically – equal length (referred to here as 'bins') (**Figure 1A**). The original Fish Event Horizon study, for example, divided the time period into 200-year blocks and placed assemblages within these based on their mid-ranges, such that an assemblage dated to AD 1150–1260 would be placed into the '13th/14th century' (AD 1200–1300) category, due to its mid-point of 1205 (Barrett et al. 2004b, 2417–2418). While this is a sensible solution in some circumstances, it has two major drawbacks. First the resolution is limited to the chosen bin width; second one must accept that the true date of an entity may fall outside the bin to which it is assigned. Reducing bin width will mitigate the former problem but exacerbate the latter; increasing the width will do the opposite.

Alternatively, one can make a judgemental assessment of 'natural breaks' in the available dating to define bins of variable width, potentially even overlapping, so as to optimise the balance between chronological resolution and the number of entities whose date ranges fall cleanly within a single bin – an approach well suited to non-frequency data such as biometrics (**Figure 1B**; e.g. Thomas et al. 2013). In historical periods these breaks are likely to be defined by a combination of round numbers (particularly ends of centuries), breaks in the pottery chronology, and major historical events. For example, London's chronology includes a number of major breakpoints such as the Boudiccan destruction horizon (AD 60/61), Hadrianic Fire (AD 122–130) and Great Fire (AD 1666), which can be identified archaeologically. The principal disadvantage of this approach is that some well-dated entities are nonetheless likely to be excluded if they straddle key breakpoints, and that it may exacerbate the inevitable tendency for apparent changes in the material record to gravitate towards major breakpoints in the chronology.

### Aoristic analysis

Another option when dealing with frequency data is to define relatively narrow chronological bins of uniform width, and then build up an overall distribution by summing the probability of each individual entity falling within each bin – an approach sometimes known as aoristic analysis (Ratcliffe 2000; Johnson 2004; see Crema 2012, 445–449 for detailed discussion). The principle here is that each entity has a total probability mass of 1, which must be divided over the length of its date range (**Figure 1C**). For example, using bin widths of 50 years, a fish bone from a stratigraphic unit with a date range of



**Figure 1: Possible methods for combining frequency data from variably dated stratigraphic contexts at three hypothetical archaeological sites (X, Y, and Z).** **A.** The mid-point method: the time period is divided into bins of (typically) uniform length – perhaps centuries – and stratigraphic contexts are assigned to the bin into which their mid-point falls, resulting in a histogram. **B.** Time blocks based on ‘natural breaks’: the time series is divided into a number of periods subjectively, based on common break-points. These periods may overlap, abut, or there may be gaps between them. Some contexts may be omitted altogether, where the date range is too long, while unusually well-dated contexts may occasionally fit entirely within two different periods – as with the second context at site Y in this example. **C.** Aoristic analysis: each context is scaled on the y-axis depending on the length of its date range, such that they each have the same area – representing a probability of 1. The resulting ‘blocks’ of probability are then superimposed on each other to produce an aoristic sum. Scaling the total area to 1 turns this into a probability distribution, which for large datasets can be used – with some caveats – as an estimator of the underlying frequency distribution.

Nb. in these examples it is assumed that we are interested in the frequency distribution of the contexts themselves, whereas in reality we are more likely to be analysing the frequency of a particular artefact or ecofact type within the contexts. In any of these methods, contexts can be weighted accordingly.

AD 1200 to AD 1350 might contribute a probability mass of 0.33 to each of three bins (1200–1250, 1250–1300, 1300–1350). Better-dated contexts will be spread over fewer bins on the  $x$  axis (time) but will contribute more on the  $y$  axis (probability density), while *area* (i.e. probability mass) remains constant. Where the dated entities actually represent multiple items they can simply be weighted accordingly, so (to continue the above example) a context with three fish bones could be given a total probability mass of 3 rather than 1 to be divided between bins. The resulting summed *probability* distribution – or *aoristic sum* – is then treated as an estimate of the *frequency* distribution, i.e. as if it were a true histogram. In theory the bin width could be set to the maximum resolution of the given dating information (to the year, for example), but in practice coarser bins may be used for the sake of computational feasibility. A version of this approach was previously used to compare frequencies of cranial versus postcranial cod bones from London (Orton et al. 2014; 2016).

There is, of course, no strict reason to assume a uniform distribution of probability between given start and end dates. The calculation of summed probability distributions (SPDs) from multiple radiocarbon dates (see e.g. Williams 2012), for example, could be viewed as a form of aoristic analysis in which the individual calibrated date distributions take the place of uniform date ranges. For dates related strictly to artefact typology, a beta distribution model may be appropriate, allowing the analyst to build in estimates for the drop-off in usage of specific types (Baxter and Cool 2016). However, where the sources of dating information are more varied, less formal, uncertainty less well defined, and/or we simply do not know or cannot quantify relative probabilities within the dating limits – a uniform distribution is typically most appropriate, following Laplace's principle of insufficient reason (Sinn 1980).

This aoristic approach may be an appropriate solution where date ranges are assumed primarily to represent *duration*, i.e. where the events represented by the dated entity are assumed to be spread over much of the given range (e.g. the gradual silting up of a ditch). It is problematic, however, where the date range largely represents *uncertainty* – that is, where the events represented by a dated entity are likely to have occurred within a relatively short space of time (e.g. the purposeful filling of a ditch), while the given start and end dates simply represent brackets within which this shorter episode can be safely said to have taken place. In the latter situation – which we would argue to be the norm for ecofactual deposits from most stratigraphic contexts – the meaning of the aoristic sum is not immediately clear. Technically, if scaled to an area of 1, it is the *probability* distribution of the true date of a single entity picked at random from the dataset: a somewhat obscure function (nb. the same is true for radiocarbon-based SPDs). Treated as an estimated *frequency* distribution, it describes a scenario that is at best one possibility out of many and at worst – e.g. for smaller datasets – may not even be possible. More pragmatically, while an aoristic sum may give a useful indication of the distribution of archaeological entities across time, it gives no indication

of the uncertainty inherent in the dating of the constituent entities, meaning that we cannot assess the reliability of the overall distribution and cannot robustly test it against other variables or against a null model (see Crema 2012, 448–451).

#### **Monte Carlo simulation**

The solution advocated by Crema, and followed here, is to apply Monte Carlo methods, i.e. simulation. As with the aoristic sum, the date range of each archaeological entity is treated as a uniform probability distribution between the stated start and end dates, but instead of summing these distributions across all entities we instead draw one date at random from within each of them – collectively representing one possible combination of true dates that may underlie the observed data – and calculate the number of entities that fall within each chronological bin at the desired resolution. This process is then repeated a large number of times – 5000 in the case study below – allowing medians and confidence intervals to be calculated for the frequency of entities in each chronological bin. On a completely different chronological scale this approach has been applied to uncertainty in zooarchaeological age-at-death analysis (Bréhard et al. 2014), but its use for integrating variably dated archaeological entities aside from  $^{14}\text{C}$  samples remains rare.

Since ecofacts of interest (in our case fish remains) derive from specific stratigraphic units, and it is typically these units that are dated rather than the individual specimens, a decision must be made on whether multiple specimens from a single unit should be simulated individually or collectively. Do we assume that they were deposited independently, potentially at different times within the date range, and hence simulate them individually? Or that they were deposited *en masse* in a single event, and hence simulate them collectively? This again comes down to the extent to which date ranges are assumed to represent duration versus uncertainty. In the below study we take the view that multiple specimens from a single context are likely to have tightly clustered dates of deposition rather than being spread out across the overall date range, and should hence be treated as a single (weighted) unit for simulation purposes. This may not always be true but is the more conservative assumption, inevitably increasing variability between simulation runs and hence broadening confidence intervals.

A key advantage of the simulation approach is that the observed results can be compared to null models by simulating 'dummy' sets based upon conservative assumptions (Crema 2012, 454). Most simply, one might set a null model of uniform frequency across a given study period and calculate the confidence interval for frequency distributions under this model, by repeating the simulation process used for the observed data but with the date limits for each entity set to be coterminous with the study period. For example, in our London study the simplest null model might assume a constant frequency of fish bones deposited between AD 1 and AD 2000. The dummy simulation would then show the extent of fluctuation that might be expected purely by chance even if this

model were correct, given the observed sample size and weightings. Where the simulated curve for the observed data falls outside the confidence band from the dummy set, fluctuations in frequency may be significant.

This method is loosely analogous to recent studies using  $^{14}\text{C}$  dates as a population proxy (e.g. Shennan *et al.* 2013; Timpson *et al.* 2014; Crema *et al.* 2016; Porčić *et al.* 2016), although in that scenario a dummy set of dates is subsequently run across the radiocarbon calibration curve, to some extent determining the shape of the resulting confidence zone (Armit *et al.* 2013). Rather than a uniform null model, such studies often use an exponential growth curve fitted as closely as possible to the empirical data, to represent the effect of site loss over time (Surovell and Brantingham 2007; Williams 2012) and/or expected human population increase (Shennan *et al.* 2013, 3). In the study below we develop a null model based instead on the distribution of sampling effort over time – representing the null hypothesis that deposition of specimens was constant over time and that the observed data are shaped only by variable research intensity (i.e. more intensive sampling of archaeological deposits of certain time periods; see following section). This removes the need for a deposit-loss model – since deposits that have been lost cannot be sampled – although a taphonomic adjustment specifically for bone diagenesis could theoretically be applied.

There are fundamental differences, however, in the nature of dates derived from mixed archaeological sources *vis-à-vis* those from radiocarbon. In the papers cited above, simulated sets of calendar dates are not sampled from the observed calibrated  $^{14}\text{C}$  dates in the same way as advocated here for archaeologically-dated entities. Rather, a single summed probability distribution (SPD) is compiled from the empirical data and compared to a set of hypothetical SPDs derived from populations simulated under the null model (**Figure 2A**). This is possible because the relationship between calendar dates and radiocarbon dates is readily modelled, being defined by the radiocarbon calibration curve: calendar dates simulated under the null model can be ‘back-calibrated’ (or ‘uncalibrated’) to give a set of hypothetical  $^{14}\text{C}$  determinations, which can then be re-calibrated and combined into hypothetical SPDs – thus realistically simulating the process by which the empirical SPD was derived, and providing a null-model-based confidence band against which it can be assessed (see Timpson *et al.* 2014 for further explanation). The equivalent with a set of archaeologically dated entities, such as our fish bones, would be to calculate the (unique) aoristic sum of the observed entities’ date ranges (which is an SPD if scaled to an area of 1), and compare this with a set of hypothetical aoristic sums based on dates simulated under the null model. But, of course, the relationship between informal archaeological date ranges and true calendar dates cannot readily be modelled, rendering the ‘back-calibration’ step impossible: we cannot probabilistically generate a set of likely *archaeological* date ranges based on a set of simulated calendar dates. For this reason, we follow Crema (2012) in using a dual-simulation approach, comparing sets of calendar dates drawn from

the empirical data and from the null model respectively (**Figure 2B**).

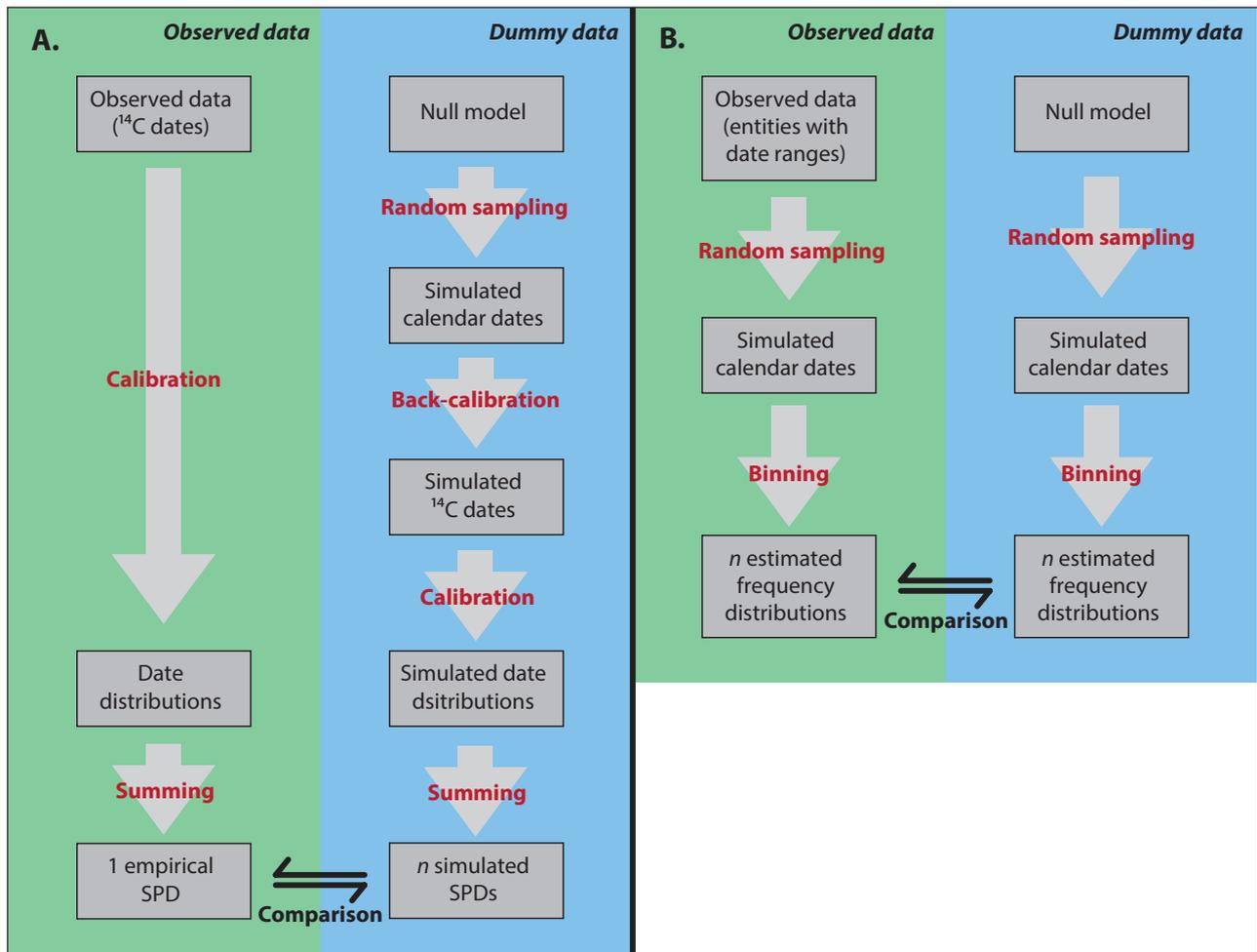
In practice, archaeological research questions often relate less to the frequency distribution of an object class *per se*, and more to the likelihood that an increase or decrease in frequency occurred at a given point in time – the Fish Event Horizon being a good example. With a simulation approach, evaluating such increases or decreases becomes a matter of calculating the rate of change in frequency between adjacent bins for each repeat, and finding the proportion of repeats in which an increase took place (Crema 2012, 454–456). Again, this can be compared with the fluctuations in frequency seen at the same point in time under a null model. Notably, this kind of rate-of-change analysis cannot be achieved using the single-simulation approach typically employed in the  $^{14}\text{C}$  literature.

### Variable research intensity and absolute frequencies

A second key challenge in chronological synthesis is that of variable archaeological research intensity, which hinders any effort to interpret changes in absolute frequency of a given object type. This is especially true for ecofacts (or artefacts) recovered mainly from wet-sieved sediment samples, as the contexts chosen for sampling – and the samples eventually processed – often reflect perceived importance of specific time periods. In English urban settlements, for example, Roman stratigraphic contexts are more likely to be sampled than those from the 19<sup>th</sup> century.

It is a well-established principle in zooarchaeology that one cannot talk reliably of absolute changes in taxonomic representation, but only of relative shifts (see Lyman 2008, 13–15). This is due to the seldom-noted compositional nature of faunal data: while fragment counts themselves are technically ‘open’, the absence of any meaningful independent reference scale effectively ‘closes’ the dataset when it comes to interpretation: the frequency of any taxon can only be measured relative to a value of which it is itself a component, typically total NISP. It is thus impossible to say whether the frequency of one taxon has increased or that of another decreased. Nor can correlations between taxonomic frequencies be taken at face value – by default taxa should be correlated positively if raw counts are compared or negatively if percentages are used (see Aitchison 1982).

To move beyond relative changes one requires an effectively independent control variable against which frequencies can be calibrated – ‘opening’ the dataset. If the species to be compared are very rare – collectively making up only a few percent of an assemblage, for example – then overall sample size may suffice for this purpose, though not technically independent of the frequencies to be compared and hence not technically correct. Fish remains, for example, might be calibrated against the frequency of other vertebrate classes. Where data on excavated/analysed volumes of sediment are available, however, an alternative is to replace raw frequency counts with measures of the *density* of bone finds in deposits. In one prehistoric



**Figure 2: Comparison between approaches to uncertainty and null-modelling of archaeological date distributions.** **A.** Single-simulation approach as typically used in the radiocarbon dates-as-data approach, in which a single empirical SPD is ultimately compared with a set of simulated dummy SPDs (simplified from Timpson et al. 2014). **B.** Double-simulation approach as set out by Crema (2012) and used here, in which a set of simulated frequency distributions based on the empirical data is compared with a matched set based upon the null model.

example, applying this technique to a millennium-long Neolithic midden sequence revealed that a sudden apparent decline in representation of one mammalian taxon was in fact an artefact of a dramatic increase in deposition of another (Russell et al. 2013, 216–218). This approach is most readily applicable where discrete samples of wet-sieved sediment have been processed for environmental remains, limiting recovery biases – for example, density in terms of grams of fish-bone per processed litre has been used to track fluctuations over time in the intensity of fishing in Lake Titicaca (Capriles et al. 2014).

Two things must be borne in mind when taking this approach. First, sediment volume is not technically independent of the frequencies of finds, since those finds contribute to the total volume; find-density data are still technically compositional – analogous, perhaps, to trace elements in ceramic or glass compositional analysis. This has troubling implications for multivariate analyses (see Aitchison et al. 2002; Baxter and Freestone 2006), but becomes a problem for comparing find deposition rates only when the finds in question make up a substantial

percentage of the sediment matrix. Bone find-density data are thus of limited value for comparing taxonomic frequencies in extremely bone-rich contexts such as fish middens or Roman urban ‘soup kitchen’ deposits.

Second, one must be clear about the chain of proxies involved: finds-per-unit-volume is used as a proxy for deposition rate, which may in turn be used as a proxy for consumption rate. The Neolithic midden trend noted above *may* thus indicate an increase in meat consumption, but it might alternatively be caused by changes in depositional practices. This is a serious concern for meta-analyses: while the inclusion of sufficiently large numbers of stratigraphic contexts can be expected to mitigate random variation in deposit types represented, the possibility of *systematic* changes over time in the underlying depositional practices must be kept in mind.

The density approach is related to a more conservative measure of abundance: ubiquity, commonly used in archaeobotany and occasionally in zooarchaeology (Popper 1988; Wright 2010; McKechnie and Moss 2016; see also Lyman 2008, 114–119). Defined as the proportion

of samples, stratigraphic entities, or even sites containing a given taxon, ubiquity is particularly useful for finds categories whose distribution tends to be extremely patchy, in the sense that finds often occur in dense concentrations that would cause instability in results using fully quantitative measures.

### Application: London and the Fish Event Horizon Dataset

The chronology of the Fish Event Horizon in London is explored here via a large fish bone dataset provided by MOLA (Museum of London Archaeology), formerly an amalgamation of the Museum of London's department of urban archaeology and department of Greater London archaeology, and now the city's largest archaeological contractor. While it would be desirable in future to expand this dataset to include other contractors, we estimate that it already accounts for approximately 40% of the relevant data from London. Crucially, MOLA have consistently operated a single relational database for all excavations since the 1990s, with some earlier projects added retrospectively. Specialist databases, including zooarchaeology, are fully integrated with tables of sites, phasing, contexts, and sediment samples, forming an extremely valuable source for meta-analyses of ecofactual data from the city (see e.g. Livarda and Orengo 2015, Orton et al. 2014; 2016; Thomas et al. 2013).

A snapshot of the MOLA database was taken in October 2013 and includes 320,797 zooarchaeological specimens recovered from 7270 chronologically phased contexts at 142 sites within the urban core of London. Fish contribute 35,187 specimens, of which 32,315 derive from 1163 wet-sieved bulk sediment samples at 84 sites. The number and overall density of specimens may appear small compared to prehistoric fish middens or to processing deposits at coastal 'producer' sites, for example, but is reasonable for an urban 'consumer' site, especially since sampling strategies in the city have rarely specifically targeted fish bones. An important aspect of the MOLA dataset is our ability to incorporate available data on processed sediment samples that *did not* produce fish remains, bringing the total number of chronologically phased samples to 5955, representing 97,471 litres of wet-sieved sediment.

All London archaeological site archives are ultimately deposited with the Museum of London, in the London Archaeological Archive. The data used in this study includes both archived and currently active (post-excavation) archaeological sites, a number of which are yet to see definitive publication with phasing and interpretations still potentially subject to change. Given this fact – and the commercial nature of the data – it is not possible to publish the full dataset here, but for the sake of reproducibility the records and fields used in this study are included in 'anonymised' form within the supplementary information, available at <https://doi.org/10.5334/oq.29.s1>.

### Analysis

We use this dataset to explore deposition rates of marine and freshwater fish bones across the Fish Event Horizon in London, employing the Monte Carlo simulation approach

outlined above (see **Figure 2B**). As is normal in British urban archaeology, dating is derived from a wide range of sources including artefact typologies, coins, dendrochronology, historically-known construction/destruction events and occasionally radiocarbon. Given the infeasibility of modelling dates from this complex range of sources, we apply the principle of insufficient reason (see above) and sample from uniform probability distributions within the stated date ranges.

We control for variable research effort in three ways:

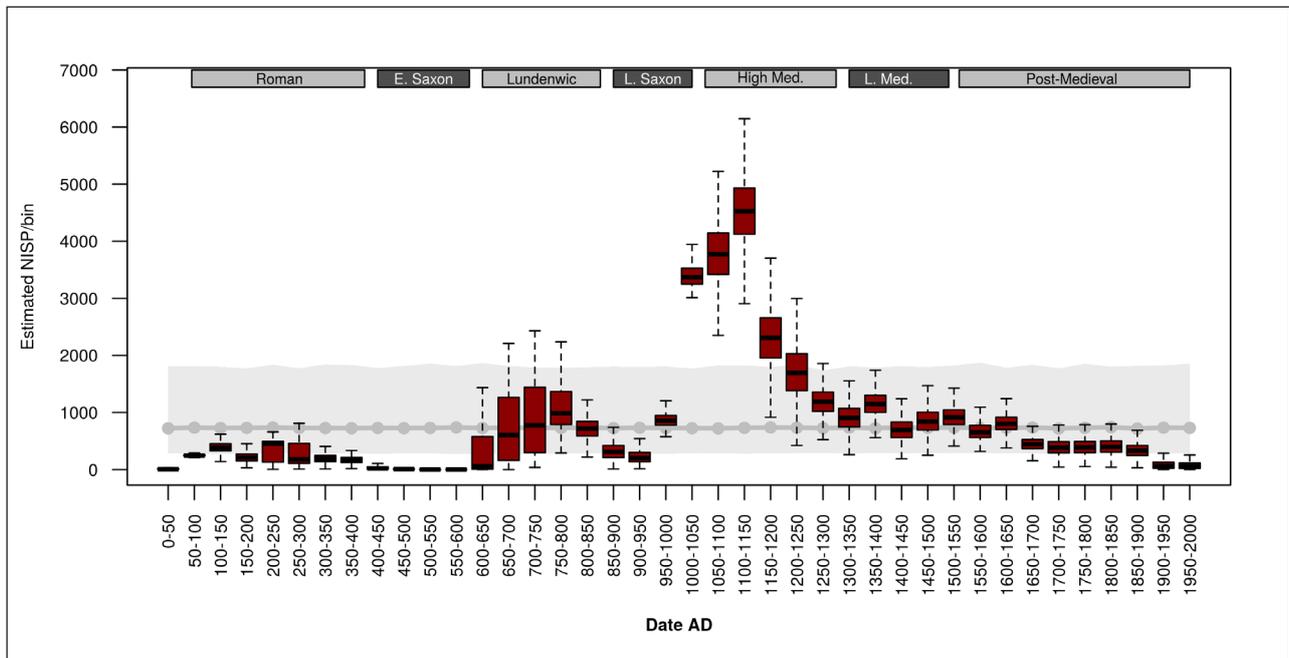
- Firstly, we use the chronological distribution of processed sediment volumes as the basis for a null model of constant deposition, against which the observed fish bone frequency data can be visually compared. Rather than sampling a dummy set from a uniform distribution, we sample it from the aoristic sum of sediment volumes – such that the probability of a specimen being placed in a given chronological bin is proportional to the volume of sediment from that bin.
- Secondly we estimate changes in bones-per-litre over time by evaluating the distributions of both sediment volumes and fish bones for each simulation run, and dividing the latter by the former for each bin. As a check, we also plot fish bone frequencies as a proportion of other vertebrate taxa recovered.
- Thirdly we calculate estimated ubiquity per chronological bin, following the same procedure as above but dividing the number of samples containing fish by the total number of samples within each bin in each simulation run.

Each metric has technical limitations, but taken together they give a robust picture of changes in fish bone deposition.

Analysis is conducted in R v.3.2.0 (R Core Team 2015) using the *archSeries* package (v.0.0.0.9003). Developed by DCO with the present study in mind, *archSeries* consists of a range of functions for creating and plotting chronological distributions using both simple aoristic and simulation methods, which we hope will be of broader utility within archaeology. For the sake of speed when performing simulations based on large datasets, *archSeries* makes heavy use of the *data.table* package (Dowle et al. 2015). At present *archSeries* only supports uniform date distributions within defined limits, but it may be expanded in future to include, for example, the beta distribution and radiocarbon-based dating. The package is accessible at <https://github.com/davidcorton/archSeries>. A copy is also included in the supplementary information at <https://doi.org/10.5334/oq.29.s1>, along with specific code for the analysis presented here.

### Results: overall frequency of fish remains

The overall distribution of fish remains from MOLA sites is shown in **Figure 3**, using the Monte Carlo simulation approach described above. Peaks are seen in the Roman, Saxon, and high medieval periods, followed by a long tail into the late and post-medieval. To some extent the



**Figure 3: Estimated chronological frequency distribution of London fish remains within the MOLA dataset (red boxplots), superimposed on dummy set generated under null hypothesis of uniformity (grey band shows 95% confidence zone; grey line shows medians).** Both plots based upon 5000 simulation runs and calculated at 50-year resolution. Boxes at top of plot show approximate durations of loose chronological periods as mentioned in the text, and should not be taken as universally accepted phases.

distribution follows fluctuations in settlement activity in London, with gaps between the Roman city (c. AD 47–410) and Saxon Lundenwic (seventh to mid ninth C AD), and again with the transition to the medieval city at the start of the 10th century. Carrying this logic over to the late and post-medieval periods, however, would suggest that activity in London faded away from about the 13th century, when in reality the city continued to grow, becoming one of the largest urban settlements in the world by the post-medieval period. Other variables are clearly influencing these results, potentially including:

1. **Changes in consumption of fish:** the issue that we hope to explore.
2. **Changes in depositional practices:** systematic changes in post-consumption treatment of fish bones could influence their chronological distribution in the dataset. The lack of post-medieval fish remains may partly reflect a move towards deposition of food waste outside London's urban core, for example, reducing the chance of fish being excavated from well-dated contexts, or indeed recovered at all.
3. **Taphonomic biases at the specimen level:** while differences in diagenetic conditions between individual contexts are likely to average out on this scale, there remains a possibility of underlying date-correlated trends in preservation – as noted for fish bones from York, for example (Harland et al. 2016).
4. **Taphonomic biases at the deposit level:** in an urban setting, the survival of deposits to the point of excavation is contingent upon subsequent

settlement activity. Widespread truncation by 19th–20th century development (Thomas 2009, 21) may be partly responsible for poor representation of post-medieval periods.

5. **Dating biases.** Apparent changes in the zooarchaeological record will tend to be drawn towards common breaks in the dating, e.g. turns of centuries, breaks in the pottery chronology, and major events. This is minimised by the approach taken here, but nonetheless inevitably causes distortions on a fine scale. Some periods may simply be better dated than others: the early Roman (first to second centuries AD) chronology in London, for example, is extremely highly resolved in comparison with the third to fifth centuries (Symonds and Tomber 1991).
6. **Excavation biases.** Which periods are well represented in the zooarchaeological record obviously depends to a great extent on which have been intensively excavated. In the MOLA dataset this is largely driven by modern-day development activity, but in other cases it might reflect research interests.
7. **Sampling biases.** Even where deposits are excavated, there may be biases in the frequency of environmental sampling, or in the subsequent processing of samples, due to research interests or to the availability of post-excavation funding.

While it is not possible to remove all potential biases, the availability of comprehensive environmental sampling information in the MOLA dataset confers an unusual degree of control over excavation, recovery, and research

bias (points 6 and 7 above). **Figure 4A** shows the aoristic sum of wet-sieved sample volumes, revealing peaks of sampling effort during the Roman, mid-Saxon, and high medieval periods. Sampling a dummy set from within this distribution shows that the observed peaks in fish frequency do coincide with the heavily sampled periods, but that sampling intensity cannot account for the relative size of those peaks (**Figure 4B**). The discrepancy between the sheer volume of processed sediment from the Roman period and the limited numbers of fish remains recovered therein is particularly striking, but the relative heights of the Saxon and high medieval peaks are also at odds with what would be expected based on sampling intensity alone.

The very wide confidence band for certain periods, particularly the mid-Saxon, become clear when individual simulation runs are plotted lines (**Figure 4C**): a small number of samples with very large fish bone assemblages are loosely dated to the Saxon period, causing instability in this part of the curve. This effect can be removed by ignoring the number of bones and counting each sample with fish remains just once, in effect adopting a presence vs. absence approach (**Figure 4D**). Plotted this way, with the *number* (rather than combined volume) of samples used as the sampling distribution for the dummy set, the underrepresentation of fish in Roman London is less dramatic, the Saxon period more-or-less matches expectations – albeit peaking slightly later than predicted – and the 11th- to 12th-century overrepresentation remains apparent. In addition, a new peak emerges during the 16th to 17th centuries.

#### **Marine versus freshwater/diadromous taxa**

**Figure 5** plots frequency distributions for marine taxa compared to those that could have been caught in freshwater. This distinction is complicated by the presence of catadromous/anadromous and estuarine species, but taxa have been grouped here following the original Fish Event Horizon papers (Barrett et al. 2004a, 2004b): eel, salmon, and other taxa that potentially migrate between fresh and saltwater are included in ‘freshwater/diadromous’, along with flounder and indeterminate right-sided flatfish that *might* have been caught in estuarine waters. Based upon total numbers of fish remains (**Figure 5A, B**), the pattern accords quite clearly with the Fish Event Horizon model: the early medieval (seventh-eighth C) peak consists almost exclusively of freshwater/diadromous fish, while the 11th to 12th-century peak also includes a substantial number of remains from definitively marine taxa.

The availability of sampling data makes it possible directly to calibrate the fish bone results for research effort, by estimating ‘catch’ per wet-sieved litre over time (**Figure 5C**), as discussed above. Chronological bins with limited sampling intensity – hence smaller samples and less reliable results – are highlighted, and it is notable that the widest confidence ranges generally occur within these bins. Taking only the better-represented periods, the lack of Roman-period fish bones is again striking, and continued near-absence of marine specimens in the eighth century contrasts with much higher levels during a broad

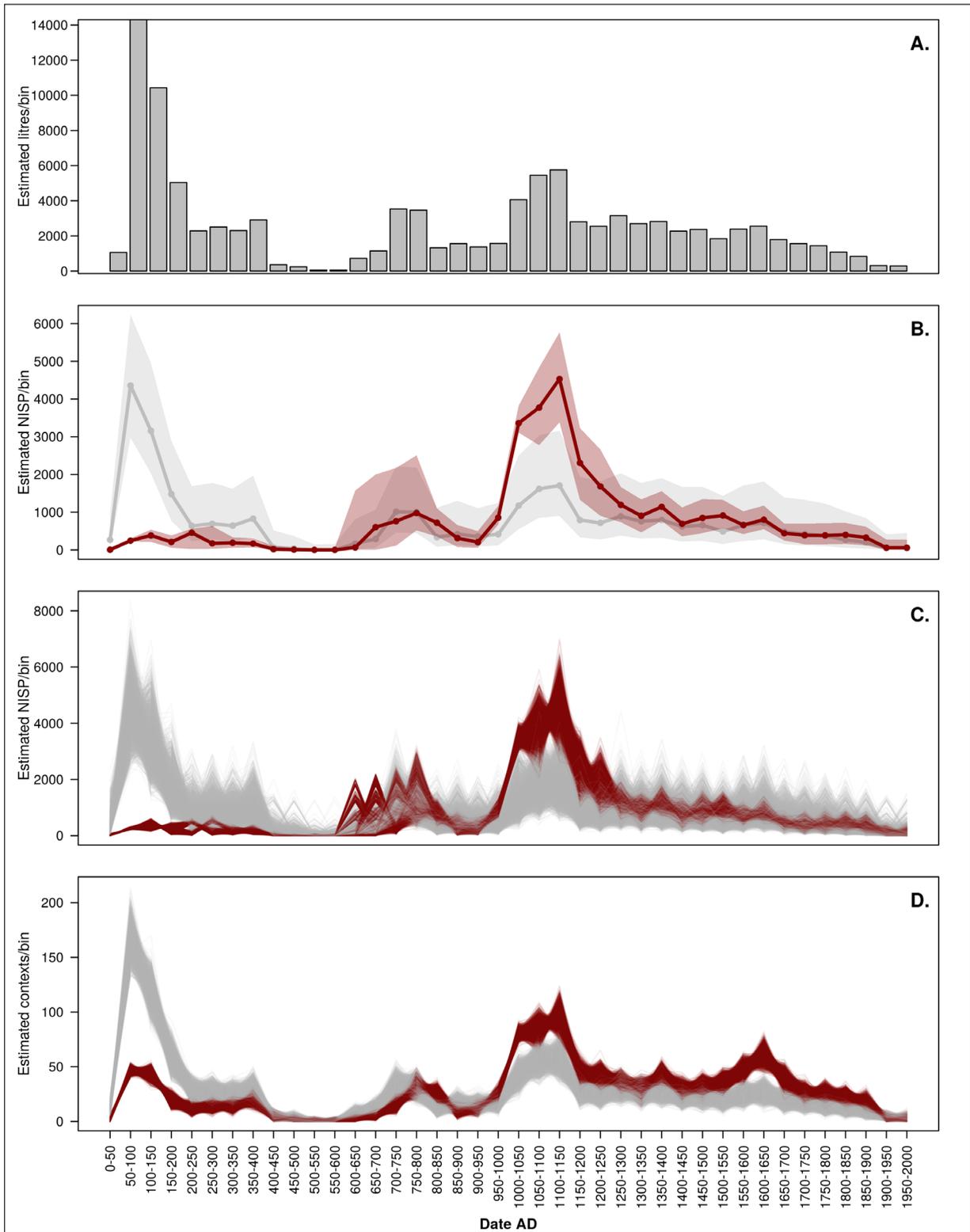
high medieval window from the 11th to 14th centuries. There is no immediate evidence for an associated decline in deposition of freshwater/diadromous fish – indeed the median count per litre for this category in the early 11th century is higher than that observed in the eighth century, although the latter is subject to considerable uncertainty. A clear decline in deposition of freshwater/diadromous fish remains is, however, apparent over the three centuries *after* the initial onset of marine fishing. In other words, the data bear out the Fish Event Horizon model, but not the suggestion that it was driven partly by declining availability of freshwater fish. The paucity of 9th- and 10th-century samples severely limits potential for refining the chronology, however.

A sharp decline in the *total* frequency of fish recovered per litre from the latter half of the 13th century onwards is puzzling, since we know historically that fish continued to be of considerable economic importance in England (Barrett 2016; Locker 2016; Galloway 2007; Kowaleski 2000; Serjeantson and Woolgar 2006) – indeed this decline coincides with archaeological evidence for the onset of large-scale imports of cod to London (Orton et al. 2014). The most likely explanation involves changes in depositional practices and a decline in the relative representation of pits among sampled contexts (**Figure 6**). The city’s growth and the development of ward-based refuse collection in the 14th century (Rawcliffe 2013, 137), might have resulted in a smaller proportion of animal remains being deposited within discrete, well-dated features within the urban core – the area in which MOLA has traditionally specialised. It is also notable that the 13th- and 16th-century surges in cod vertebrae reported by Orton et al. (2014, 523) were most apparent in data from sources other than MOLA – although this appears partly to reflect identification-level biases for vertebrae that would not affect the broad categories used here.

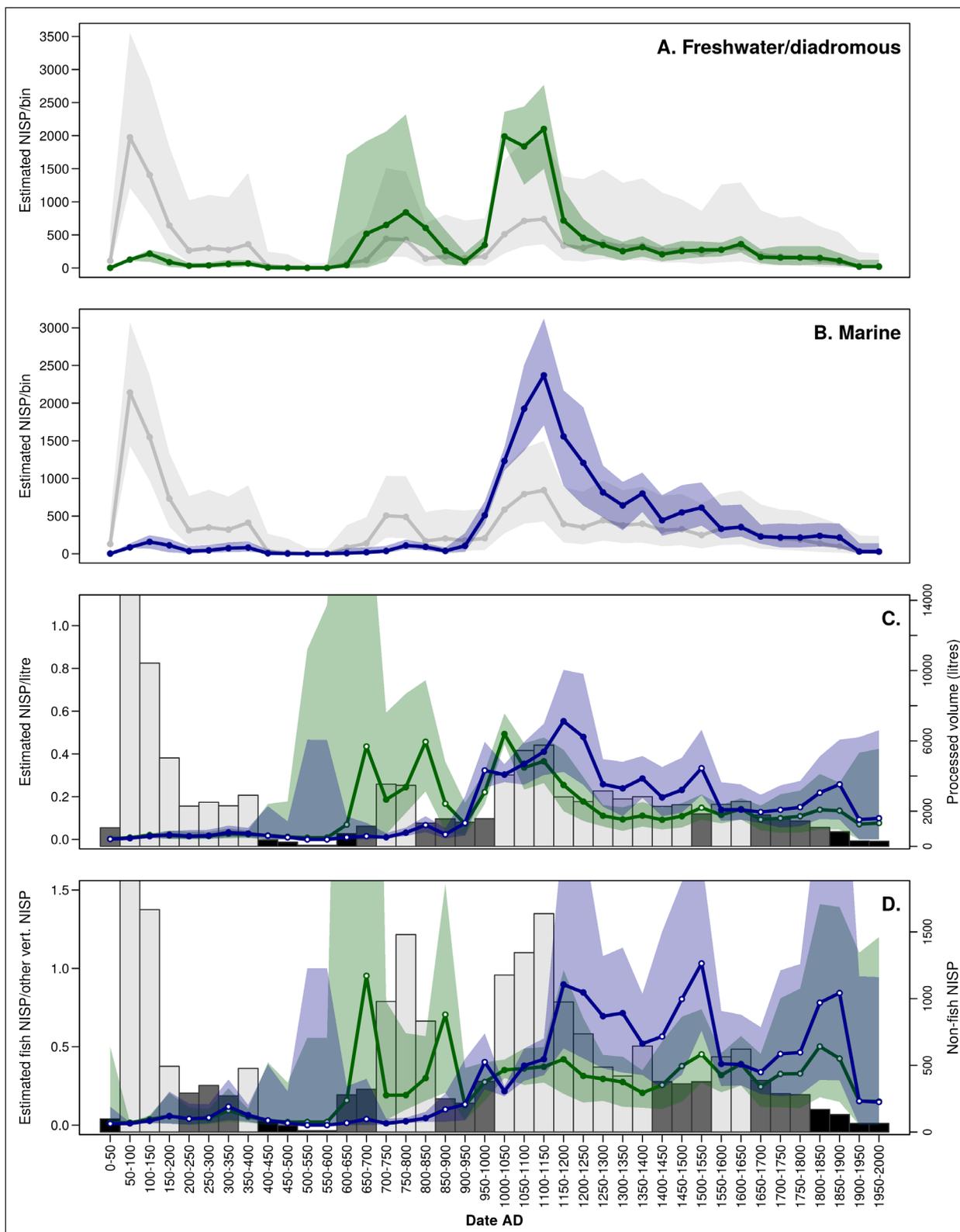
The possibility of a shift in the depositional practices represented within the dataset is supported by **Figure 5D**, in which fishbone frequencies are normed against the combined frequency of other vertebrate classes from wet-sieved samples, rather than against sample volumes. The overall picture is reassuringly similar to **Figure 5C**, showing a freshwater/diadromous-dominated Saxon period followed by a mixed 11th- to 12th-century assemblage. Normed in this way, however, the post-1250 decline in total fish remains is much less apparent. Taken together with **Figure 5C**, this indicates that the late medieval drop in fishbones per litre has more to do with the overall quantity of bone within the samples – and therefore with depositional practices and context types – than with the specific contribution of fish.

#### **Rates of change over time**

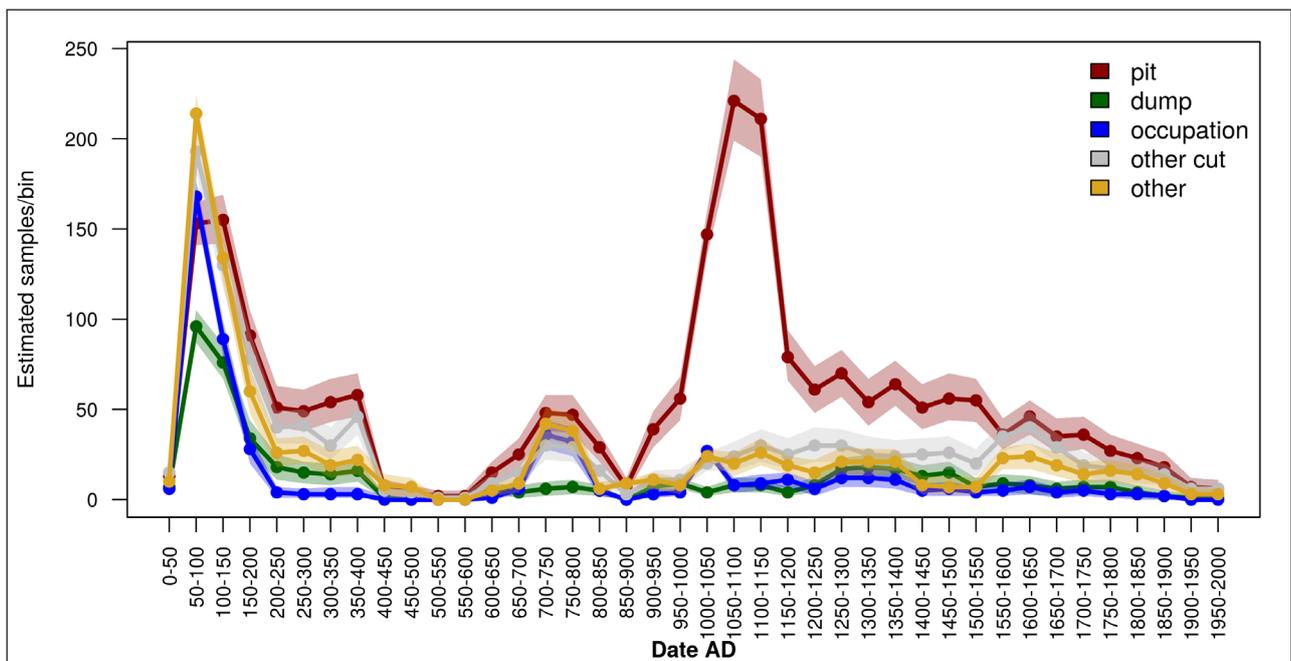
**Figure 7** plots simulated rates of change between bins, comparing the observed frequencies of the two fish categories with dummy sets based on sample volumes and on total NISP of other vertebrate taxa. Trends are plotted at three levels of bin resolution: 50, 100, and 200 years. Starting with marine taxa (**Figure 7A–C**), an increase fitting the Fish Event Horizon model is apparent in all cases but only



**Figure 4: Applying a sampling intensity-based null model to the London data.** **A.** Aoristic sum of processed environmental sample volumes within the MOLA dataset, using 50-year bins. **B.** Estimated chronological frequency distribution of London fish remains within the MOLA dataset (red), with dummy set based upon the distribution of processed sampled volumes (grey). The latter represents the null hypothesis that deposition and bone preservation are constant, with observed frequency based entirely on sampling intensity. In each case, coloured band represents 95% confidence zone and line represents medians. Both sets based upon 5000 simulation runs and calculated at 50-year resolution. **C.** Data as pane B, but with each simulation run plotted as a single semi-opaque line. Sharp peaks and troughs within 7<sup>th</sup>–8<sup>th</sup> centuries suggest that wide confidence intervals at this point are due to individual large contexts, whose simulated date has a disproportionate effect on the overall distribution. **D.** Estimated chronological frequency distribution of London contexts containing fish, set against a null model based on sampling intensity (methodology as pane C).



**Figure 5: Comparison of chronological distributions of marine and ‘freshwater/diadromous’ (see text for definitions) fish within the MOLA dataset. A.** Estimated frequency distributions for freshwater/diadromous fish remains (green) with dummy set based on sampling intensity (grey). **B.** Estimated frequency distributions for marine fish remains (blue) with dummy set based on sampling intensity (grey). **C.** Comparison of ‘catch per litre’ between freshwater/diadromous (green) and marine (blue) fish, superimposed on aortic sum of sample volumes. White dots and grey bars represent 50-year bins with fewer than 2000 processed litres; white dots and black bars represent 50-year bins with fewer than 1000 processed litres. **D.** Comparison between freshwater/diadromous and marine fish remains in terms of NISP of relevant fish category divided by NISP of non-fish vertebrate taxa. White dots and grey bars represent 50-year bins with non-fish NISP below 400; white dots and black bars represent 50-year bins with non-fish NISP below 200. All plots based on 5000 simulation runs.



**Figure 6: Estimated chronological frequency distributions for the main environmentally-sampled context types in the MOLA dataset.** Coloured bands represents 95% confidence zones. Based on 5000 simulation runs and calculated at 50-year resolution.

emerges clearly from the 95% dummy confidence zone at the 200-year resolution, occurring between the 9th/10th and 11th/12th century bins as expected. At the 50-year resolution an increase in frequency is seen between each of the 10th- and 11th-century bins, but none of these is clearly beyond the dummy zone – suggesting either that the Fish Event Horizon in London took the form of a more gradual increase over much of this period, or that the data are simply not fine-grained enough to reveal its timing at this resolution. When the dummy set is based on fluctuations in abundance of other vertebrate classes (**Figure 7D–F**) a broadly consistent pattern emerges: once marine taxa emerge in appreciable numbers from the 10th or 11th century, they subsequently track the frequency of other vertebrates relatively closely.

Turning to the freshwater/diadromous category (**Figure 7G–I**), there is no decrease in frequency coincident with the appearance of marine taxa. Rather, there is a sharp *increase* between the 10th and 11th centuries (visible at all three resolutions) that is at the upper end of what would be expected based on sampling intensity, and almost perfectly meets expectations based on other vertebrate classes. A subsequent sharp decrease may be significant by comparison to sample volumes, but is very much in line with trends in other classes. The data thus provide little support for the suggestion that the Fish Event Horizon coincided with a decrease in availability of freshwater/diadromous taxa.

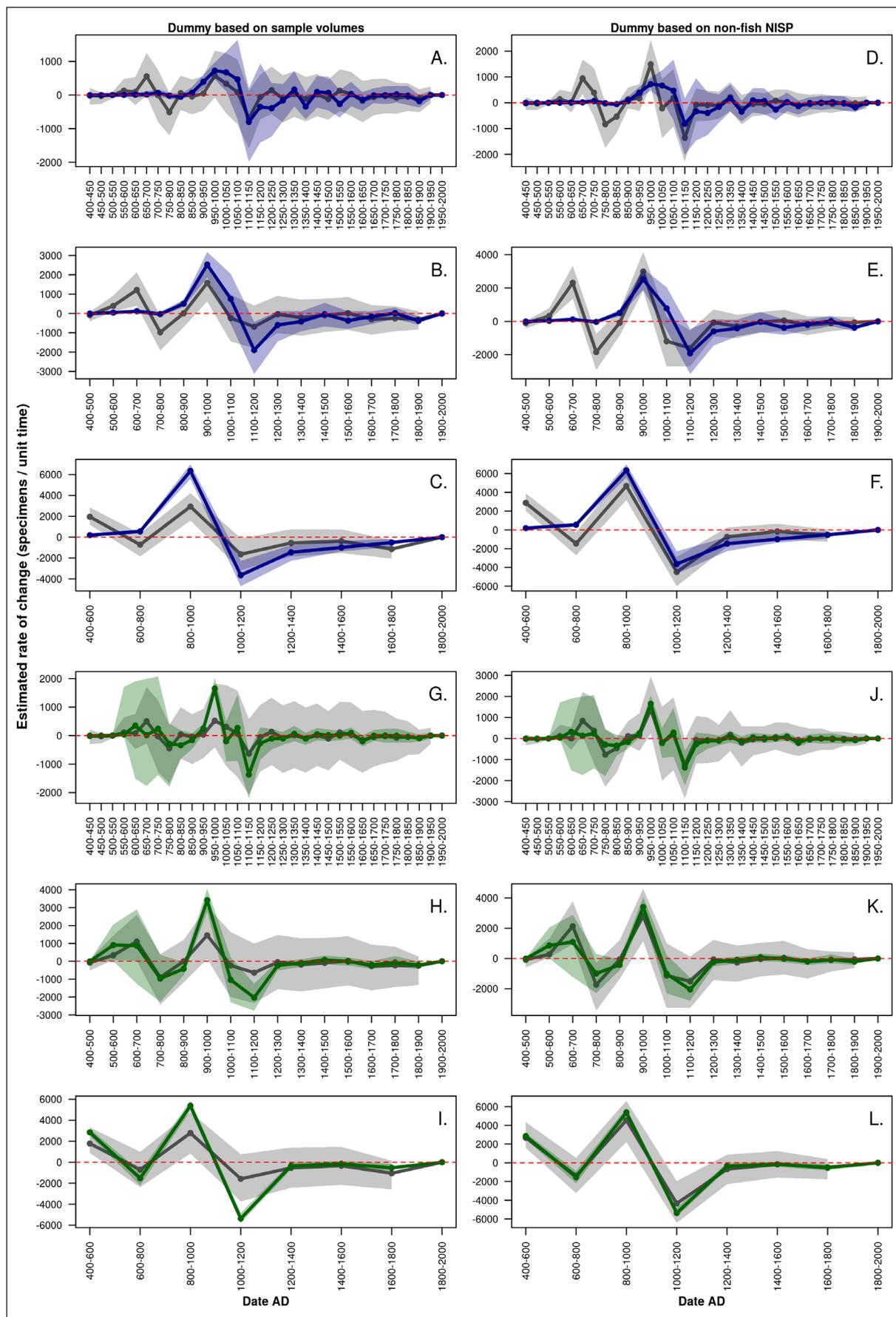
#### **Ubiquity and diversity**

The frequency-based, fully quantitative metrics applied thus far have two limitations: occasional dense deposits of bones may distort results – as seen above in Saxon London (**Figure 5C**) – while inter-taxonomic differences in the number of recoverable elements introduce

biases (Wheeler and Jones 1989, 152). **Figure 8** plots two measures based upon presence, rather than frequency, of remains in samples. First, the overall ubiquity of freshwater/diadromous and of marine fish by time (**Figure 8A**) shows a rather different pattern than the frequency-based plots. Leaving aside the poorly-represented bins, there is a substantial increase in the ubiquity of *both* groups between the 8th and 10th centuries, but also between the earlier and later eighth century. Overall, the two categories track each other very closely, with the median estimate for each curve falling within the 95% confidence interval of the other at all times. If one looks at the typical number of species from each category in a sample, however – effectively calculating mean taxonomic richness per sample within each category – the switch from freshwater/diadromous to marine taxa is again apparent (**Figure 8B**). Comparing these metrics with the frequency data above, the Fish Event Horizon appears to have entailed more widespread deposition of *both* fish categories in London, but with the typical quantities of marine specimens increasing and those of freshwater/diadromous specimens decreasing. Again, there is no indication that an overall decline in deposition of the latter group coincided with the increase in marine remains.

#### **Comparing ‘freshwater/diadromous’ categories**

A detailed analysis of changes at species level is beyond the scope of this paper, but it is worth briefly unpacking the ‘freshwater/diadromous’ category (**Figure 9**). The majority of specimens here are migratory, with this sub-category accounting for most of the non-marine fish bone from the 11th and 12th centuries in particular. These are primarily catadromous eels (*Anguilla anguilla*), while anadromous Atlantic salmon (*Salmo salar*) are present in



**Figure 7: Simulated rates of change in frequency over time within the MOLA dataset, calculated at 50, 100, and 200 year bandwidths. A–F: Marine fish remains; G–L: Freshwater/diadromous fish remains. Dummy sets (in grey) are based variously on processed sample volumes (A–C, G–I) and on frequencies on non-fish vertebrate taxa (D–F, J–L). All plots based on 5000 simulation runs.**

very small numbers throughout the sequence rather than showing the marked decline recently noted for medieval Belgium, Netherlands, and northern France and attributed to watermill construction (Lenders et al. 2016). Given the unusually large number of vertebrae in the eel skeleton their importance is likely to be exaggerated to some extent (e.g. Enghoff 1986), but is nonetheless clearly substantial. While it is possible that this trend reflects diadromous taxa being caught at sea, it is more likely (along with the estuarine ‘freshwater/marine’ group) to reflect fisheries in the lower reaches of the Thames, particularly using fixed structures (Galloway 2015). A drop in migratory fish numbers – again mainly eel – into the later twelfth century is more dramatic than that observed for other taxa, meanwhile, and merits more detailed study in future.

### Conclusions

This paper set out to assess how suddenly the Fish Event Horizon manifested in London, and whether the increase in marine taxa involved a concomitant *absolute* decrease in deposition of freshwater and diadromous taxa that might potentially be linked to overexploitation or habitat destruction.

The first aim is hindered by limited data from the 9th and 10th centuries, at least within the MOLA dataset: while there is some indication that frequencies of marine fish were already on the rise in the latter half of the 10th century, this is based on limited samples and uncertain dating and should be treated with caution. By the time London re-emerges as a major urban settlement in the 11th century marine taxa are clearly present, contributing probably a little under half of the total fish remains – consistent with the wider national picture. This appears to be an ongoing trend, with the representation of marine taxa increasing markedly into the 12th century in terms of frequency (**Figure 5C–D**) and average diversity (**Figure 8B**), though not of ubiquity (**Figure 8A**). There is also some sign that both ubiquity and average diversity of marine taxa may have already been increasing by the latter half of the eighth century, although this is not clearly apparent in the frequency data.

Turning to the second aim, our analysis strongly suggests that there was no immediate drop-off in deposition of freshwater/diadromous remains coincident with the Fish Event Horizon: whether normed by sample volumes or by abundance of other vertebrate classes, frequency data show no clear change in deposition of this category between the well-sampled 8th and 11th centuries. Ubiquity, meanwhile, shows an *increase* in representation of non-marine fish between these windows. It is not until the 12th century that deposition of freshwater/diadromous taxa clearly falls behind that of marine fish, and the extent to which this represents a decline in the former rather than an increase in the latter depends on how the data are normed. Find-density data do indicate a rapid absolute decline in freshwater/diadromous fish from an 11th-century peak through to the late medieval period (**Figure 5C**), while frequency relative to other classes suggests at most a subtle decline (**Figure 5D**). In either case, any decline appears to postdate the Fish Event Horizon,

and hence cannot be invoked as a cause of that phenomenon: we find no evidence to support the notion that the switch to marine fisheries was driven in part by depletion of freshwater resources.

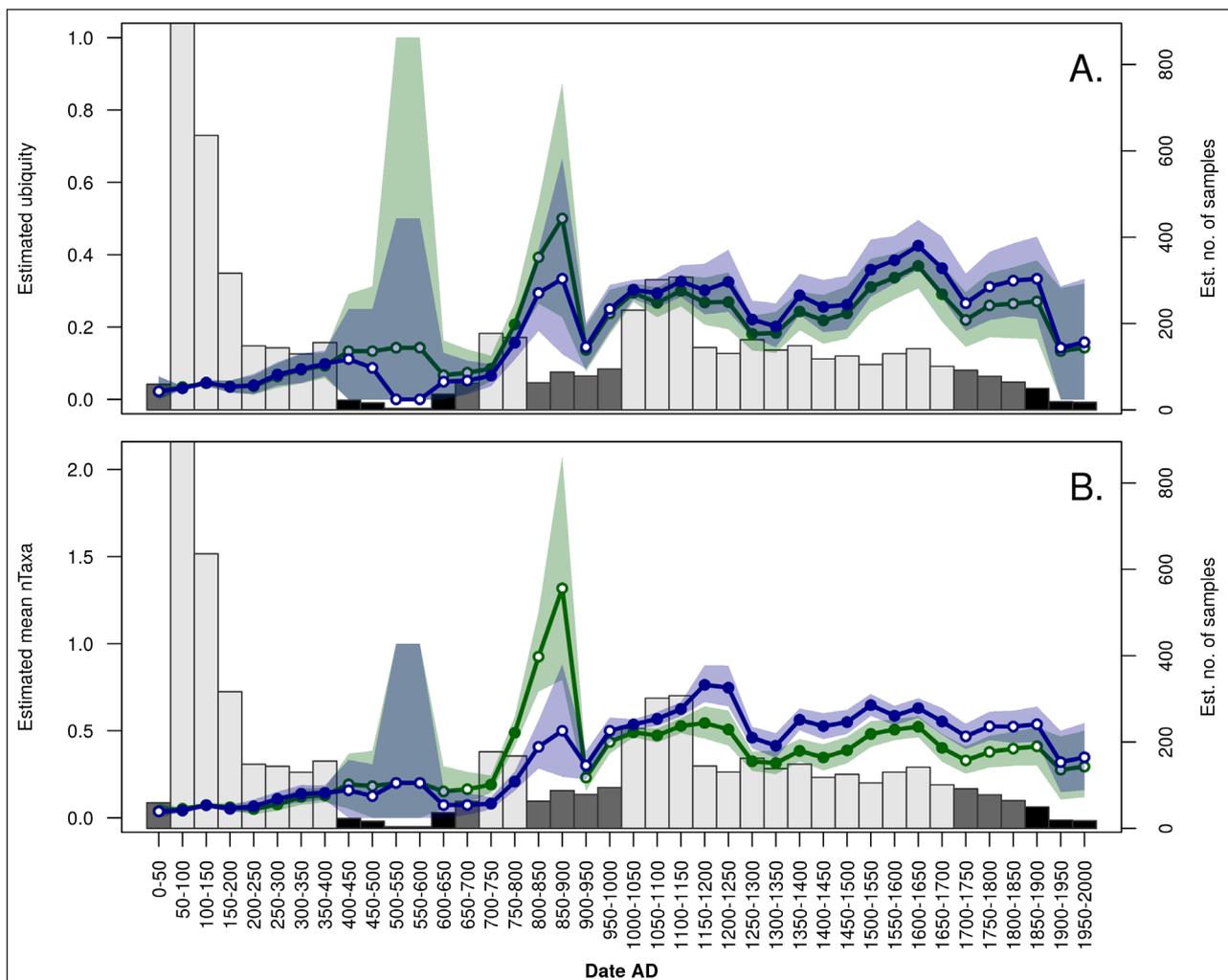
On the other hand, unpacking the ‘freshwater/diadromous’ category reveals a relative shift towards diadromous species (**Figure 9**), particularly eel. While we consider it unlikely that this mainly represents marine catches of these species, it does suggest developments in the exploitation of the Thames river system – likely including changes in the relative importance of estuarine fisheries – that would benefit from systematic archaeological study in future. Increasing elite control and regulation of inland fisheries may have been important here after AD 1000 (Hoffmann 1996, 653; Barrett et al. 2004a, 628), as might flooding and environmental change in the Thames estuary in the later medieval period (Galloway 2009; 2013).

Regarding other time periods, our analysis supports Locker’s (2007, 157) observation that fish, and especially marine fish, are less common in Roman Britain than sometimes assumed, despite the partially marine human isotopic signatures noted for this period (Müldner 2013).

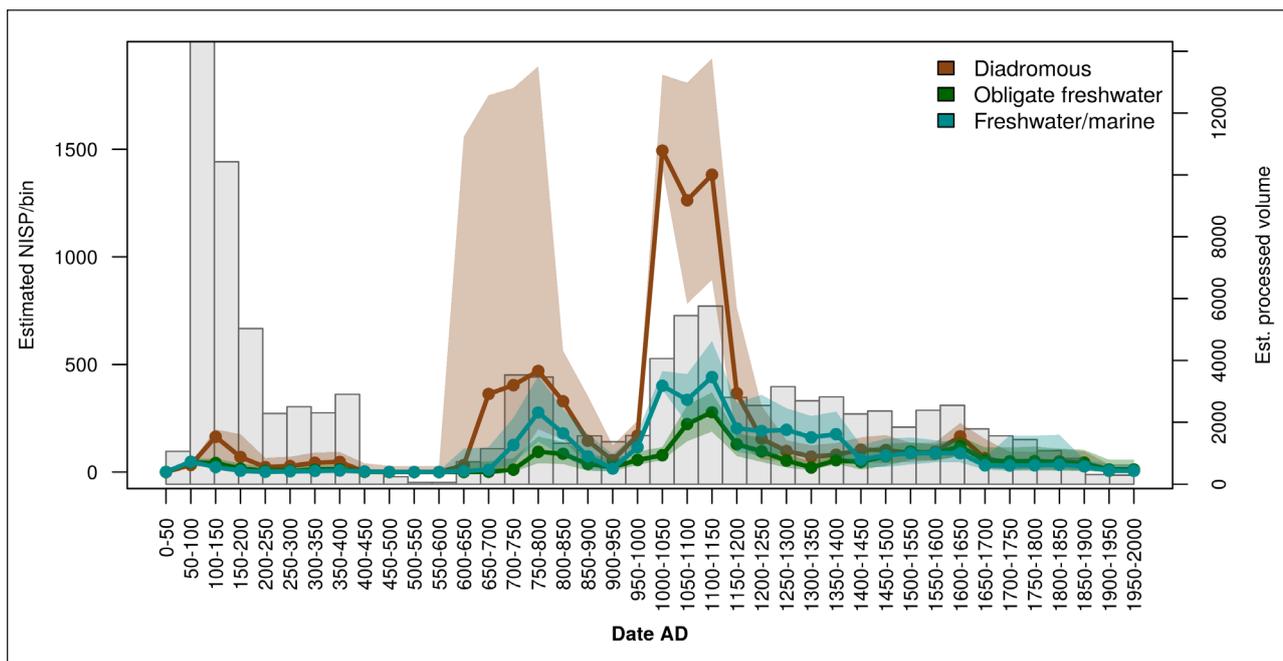
Methodologically, we set out to demonstrate techniques for integrating data from stratigraphic entities with varying date limits and chronological resolution into overall time series, and calibrating those time series for research intensity. Our solution to the first problem is straightforward but effective, borrowing as it does from proven approaches in other areas of archaeology. By applying Monte Carlo methods, following Crema (2012), we are able not only to integrate zooarchaeological data from across London’s history, but also to visualise our degree of confidence in the trends that emerge.

Our solution to the second problem is likely to be more contentious. Using sampling intensity to calibrate urban environmental archaeological results has considerable potential, as we believe we have demonstrated here, but also significant limitations. It is unreliable for periods in which the degree of sampling effort is low – although in fairness this hinders *any* approach to the data, and our method at least reveals such periods clearly. More problematic is the fact that it is vulnerable to changes in depositional practices and in spatial organisation of the settlement *vis-à-vis* excavation patterns. The latter could be explored further through a combined spatio-temporal approach, although the London fish dataset might not be large enough to support such a study.

When working with relatively rare taxonomic groups, such as the fish in our study, this risk of changing deposit type representation may be mitigated by using combined frequency of other taxa as an alternative control variable alongside sampling intensity. In our case, this comparison helped to reveal a discrepancy in late medieval fish abundance trends that we interpret in terms of the changing nature of depositional contexts sampled, but which might otherwise have been taken to represent a rapid decline in deposition. This additional check is only possible, of course, where all the data derive from



**Figure 8: Simulated ubiquity (A) and diversity (B) of marine (blue) and freshwater/diadromous (green) fish taxa in London over time, superimposed on aoristic sum of processed environmental samples.** White dots and grey bars represent 50-year bins with fewer than 100 samples; white dots and black bars represent 50-year bins with fewer than 50 samples. Both plots based on 5000 simulation runs.



**Figure 9: Estimated chronological frequency distributions for broad categories of fish within the 'freshwater/diadromous' group, superimposed on aoristic sum of processed sample volumes.** Based on 5000 simulation runs.

the same sampling process, and where this process is unlikely to be biased between the taxa under study and those used as the control – in the case of fish it is thus unlikely to be applicable post-hoc to published assemblages (see Barrett *et al.* 2004b, 628). Nor is it applicable where the taxa in question are relatively abundant within the overall assemblage, in which case sampled volumes remain the only potential external control on frequencies. While potentially powerful, our catch-per-unit-effort approach should thus be applied with some caution.

Any assessment of trends in taxonomic frequencies at a settlement as large, complex, and frequently excavated as London is inevitably fraught with complications. Nonetheless, by integrating zooarchaeological data from across the city with data on sampling intensity, using a range of innovative approaches and metrics, we have been able to make a significant contribution to understanding of a crucial development in medieval economic and environmental history – the Fish Event Horizon – as manifest in London. Most importantly, we have shown that the marked increase in marine fishing around AD 1000 *predates* any visible drop-off in freshwater fish consumption, and hence cannot have been driven by depletion of inland fisheries. Rather, our results support the argument that changes were driven by rising overall demand and/or increased supply of marine species.

Finally, the freely available R package developed for this project, *archSeries*, will enable archaeologists in a wide variety of contexts, both within and beyond urban environmental archaeology, to utilise the methods advocated in this study.

### Additional Files

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

- **Additional file 1:** Data and R code files related to this study. <https://doi.org/10.5334/oq.29.s1>

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### Competing Interests

The authors have no competing interests to declare.

### References

- Aitchison, J** 1982 The statistical analysis of compositional data. *Journal of the Royal Statistical Society. Series B, Statistical Methodology*, 44(2): 139–177.
- Aitchison, J, Barceló-Vidal, C and Pawlowsky-Glahn, V** 2002 Some comments on compositional data analysis in archaeometry, in particular the fallacies in Tangri and Wright's dismissal of logratio analysis. *Archaeometry*, 44(2): 295–304. DOI: <https://doi.org/10.1111/1475-4754.t01-1-00061>
- Armit, I, Swindles, G T and Becker, K** 2013 From dates to demography in later prehistoric Ireland? Experimental approaches to the meta-analysis of large  $^{14}\text{C}$  data-sets. *Journal of Archaeological Science*, 40(1): 433–438. DOI: <https://doi.org/10.1016/j.jas.2012.08.039>
- Astill, G** 2009 Medieval towns and urbanization. In: Gilchrist, R and Reynolds, A (Eds.) *Reflections: 50 years of medieval archaeology, 1957–2007*. Leeds: Maney, pp. 255–270.
- Barbier, E B** 2011 *Scarcity and Frontiers: how economies have developed through natural resource exploitation*. Cambridge: Cambridge University Press.
- Barrett, J H** 2016 Medieval sea fishing, AD 500–1500: chronology, causes and consequences. In: Barrett, J H and Orton, D C (Eds.) *Cod and Herring: the archaeology and history of medieval sea fishing*. Oxford: Oxbow, pp. 250–272.
- Barrett, J H, Locker, A M and Roberts, C M** 2004a Dark age economics revisited: the English fish bone evidence AD 600–1600. *Antiquity*, 78(301): 618–636. DOI: <https://doi.org/10.1017/S0003598X00113262>
- Barrett, J H, Locker, A M and Roberts, C M** 2004b The origins of intensive marine fishing in medieval Europe: the English evidence. *Proceedings of the Royal Society of London B: Biological Sciences*, 271(1556): 2417–2421. DOI: <https://doi.org/10.1098/rspb.2004.2885>
- Barrett, J H, Orton, D C, Johnstone, C, Harland, J, Van Neer, W, Eryvynck, A, Roberts, C, Locker, A, Amundsen, C, Enghoff, I B, Hamilton-Dyer, S, Heinrich, D, Hufthammer, A K, Jones, A K G, Jonsson, L, Makowiecki, D, Pope, P, De Roo, T and Richards, M** 2011 Interpreting the expansion of sea fishing in medieval Europe using stable isotope analysis of archaeological cod bones. *Journal of Archaeological Science* 38(7): 1516–24. DOI: <https://doi.org/10.1016/j.jas.2011.02.017>
- Baxter, M J and Cool, H E M** 2016 Reinventing the wheel? Modelling temporal uncertainty with applications to brooch distributions in Roman Britain. *Journal of Archaeological Science*, 66: 120–127. DOI: <https://doi.org/10.1016/j.jas.2015.12.007>
- Baxter, M J and Freestone, I C** 2006 Log-ratio compositional data analysis in archaeometry. *Archaeometry*, 48(3): 511–531. DOI: <https://doi.org/10.1111/j.1475-4754.2006.00270.x>
- Bevan, A, Conolly, J, Hennig, C, Johnston, A, Quercia, A, Spencer, L and Vroom, J** 2013 Measuring

chronological uncertainty in intensive survey finds: a case study from Antikythera, Greece. *Archaeometry*, 55(2): 312–328. DOI: <https://doi.org/10.1111/j.1475-4754.2012.00674.x>

- Bréhard, S, Radu, V, Martin, A, Hanot, P, Popovici, D and Bălăşescu, A** 2014 Food supply strategies in the Romanian Eneolithic: sheep/goat husbandry and fishing activities from Hârşova Tell and Borduşani-Popină (5th Millennium BC). *European Journal of Archaeology*, 17(3): 407–433. DOI: <https://doi.org/10.1179/1461957113Y.0000000051>
- Capriles, J M, Moore, K M, Domic, A I and Hastorf, C A** 2014 Fishing and environmental change during the emergence of social complexity in the Lake Titicaca Basin. *Journal of Anthropological Archaeology*, 34: 66–77. DOI: <https://doi.org/10.1016/j.jaa.2014.02.001>
- Crema, E R** 2012 Modelling temporal uncertainty in archaeological analysis. *Journal of Archaeological Method and Theory*, 19(3): 440–461. DOI: <https://doi.org/10.1007/s10816-011-9122-3>
- Crema, E R, Bevan, A and Lake, M W** 2010 A probabilistic framework for assessing spatio-temporal point patterns in the archaeological record. *Journal of Archaeological Science*, 37(5): 1118–1130. DOI: <https://doi.org/10.1016/j.jas.2009.12.012>
- Crema, E R, Habu, J, Kobayashi, K and Madella, M** 2016 Summed probability distribution of <sup>14</sup>C dates suggests regional divergences in the population dynamics of the Jomon period in eastern Japan. *PLoS ONE*, 11(4): e0154809. DOI: <https://doi.org/10.1371/journal.pone.0154809>
- Dowle, M, Srinivasan, A, Short, T and Lianoglou, S** 2015 *data.table: extension of 'data.frame'*. <http://CRAN.R-project.org/package=data.table>.
- Dyer, C** 2002 *Making a Living in the Middle Ages*. London: Yale University Press.
- Edinborough, K, Crema, E, Kerig, T and Shennan, S** 2015 An ABC of lithic arrowheads: a case study from southeastern France. In Brink, K, Hydén, S, Jennbert, K, Larsson, L and Olausson, D (Eds.) *Neolithic Diversities: perspectives from a conference in Lund, Sweden*. Lund: Department of Archaeology and Ancient History, pp. 213–223.
- Enghoff, I B** 1986 Freshwater fishing from a sea-coast settlement – the Ertebølle *locus classicus* revisited. *Journal of Danish Archaeology*, 5(1): 62–76. DOI: <https://doi.org/10.1080/0108464X.1986.10589958>
- Ervynck, A, Van Neer, W and Pieters, M** 2004 How the north was won (and lost again): historical and archaeological data on the exploitation of the North Atlantic by the Flemish fishery. In Housely, R A and Coles, G M (Eds.) *Atlantic Connections and Adaptations: economies, environments and subsistence in lands bordering the North Atlantic*. Oxford: Oxbow, pp. 230–239.
- Galik, A, Haidvogel, G, Bartosiewicz, L, Gutti, G and Jungwirth, M** 2015 Fish remains as a source to reconstruct long-term changes of fish communities in the Austrian and Hungarian Danube. *Aquatic Sciences*, 77(3): 1–18. DOI: <https://doi.org/10.1007/s00027-015-0393-8>
- Galloway, J A** 2007 Ripiers and the supply of fresh sea-fish to later medieval London. Presented to Diet Group, Oxford, UK on 12 May 2007.
- Galloway, J A** 2009 Storm flooding, coastal defence and land use around the Thames estuary and tidal river c.1250–1450. *Journal of Medieval History*, 35(2): 171–188. DOI: <https://doi.org/10.1016/j.jmedhist.2008.12.001>
- Galloway, J A** 2013 Coastal flooding and socio-economic change in eastern England in the later Middle Ages. *Environment and History*, 19(2): 173–207. DOI: <https://doi.org/10.3197/096734013X13642082568615>
- Galloway, J A** 2015 London and the Thames Estuary in the later middle ages: economic and environmental change. In Wilkin, A, Naylor, J, Keene, D and Bijsterveld, A J A (Eds.) *Town and Country in Medieval North Western Europe: dynamic interactions*. Turnhout: Brepols, pp. 119–144. DOI: <https://doi.org/10.1484/M.TMC-EB.5.107296>
- Galloway, J A and Murphy, M** 1991 Feeding the City: medieval London and its agrarian hinterland. *The London Journal*, 16(1): 3–14. DOI: <https://doi.org/10.1179/ldn.1991.16.1.3>
- Garstang, W** 1900 The impoverishment of the sea. A critical summary of the experimental and statistical evidence bearing upon the alleged depletion of the trawling grounds. *Journal of the Marine Biological Association of the United Kingdom*, 6(1): 1–69. DOI: <https://doi.org/10.1017/S0025315400072374>
- Häberle, S, Fuller, B T, Nehlich, O, Van Neer, W, Schibler, J and Plogmann, H H** 2016a Inter- and intraspecies variability in stable isotope ratio values of archaeological freshwater fish remains from Switzerland (11th–19th centuries AD). *Environmental Archaeology*, 21(2): 119–132. DOI: <https://doi.org/10.1179/1749631414Y.0000000042>
- Häberle, S, Nehlich, O, Fuller, B T, Schibler, J, Van Neer, W and Plogmann, H H** 2016b Carbon and nitrogen isotopic ratios in archaeological and modern Swiss fish as possible markers for diachronic anthropogenic activity in freshwater ecosystems. *Journal of Archaeological Science: Reports*, 10: 411–423. DOI: <https://doi.org/10.1016/j.jasrep.2016.10.012>
- Harland, J F, Jones, A K G, Orton, D C and Barrett, J H** 2016 Fishing and fish trade in medieval York: the zooarchaeological evidence. In Barrett, J H and Orton, D C (Eds.) *Cod and Herring: the archaeology and history of medieval sea fishing*. Oxford: Oxbow, pp. 172–204.
- Hoffmann, R C** 1996 Economic development and aquatic ecosystems in Medieval Europe. *The American Historical Review*, 101(3): 631–669. DOI: <https://doi.org/10.1086/ahr/101.3.631>
- Hoffmann, R C** 2001 Frontier foods for late Medieval consumers: culture, economy, ecology. *Environment*

- and *History*, 7(2): 131–167. DOI: <https://doi.org/10.3197/096734001129342432>
- Hoffmann, R C** 2002 Carp, cods, connections: new fisheries in the medieval European economy and environment. In Henninger-Voss, M J (Ed.) *Animals in Human Histories: the mirror of nature and culture*. Rochester, NY: University of Rochester Press, pp. 3–55.
- Hoffmann, R C** 2004 A brief history of aquatic resource use in medieval Europe. *Helgoland Marine Research*, 59(1): 22–30. DOI: <https://doi.org/10.1007/s10152-004-0203-5>
- Johnson, I** 2004 Aoristic analysis: seeds of a new approach to mapping archaeological distributions through time. In: Ausserer, K F, Börner, W, Goriany, M and Karlhuber-Vöckl, L (Eds.) [*Enter the past*] *the E-way into the four dimensions of cultural heritage: CAA2003*. Oxford: Archaeopress, pp. 448–452.
- Kowaleski, M** 2000 The expansion of the south-western fisheries in late medieval England. *The Economic History Review*, 53(3): 429–454. DOI: <https://doi.org/10.1111/1468-0289.00166>
- Kowaleski, M** 2016 The early documentary evidence for the commercialisation of the sea fisheries in medieval Britain. In: Barrett, J H and Orton, D C (Eds.) *Cod and Herring: the archaeology and history of medieval sea fishing*. Oxford: Oxbow, pp. 23–41.
- Langdon, J** and **Masschaele, J** 2006 Commercial activity and population growth in medieval England. *Past and Present*, 190(1): 35–81. DOI: <https://doi.org/10.1093/pastj/gtj005>
- Lenders, H J R, Chamuleau, T P M, Hendriks, A J, Lauwerier, R C G M, Leuven, R S E W and Verberk, W C E P** 2016 Historical rise of water-power initiated the collapse of salmon stocks. *Nature Scientific Reports*, 6: 29269. DOI: <https://doi.org/10.1038/srep29269>
- Livarda, A** and **Orengo, H A** 2015 Reconstructing the Roman London flavourscape: new insights into the exotic food plant trade using network and spatial analyses. *Journal of Archaeological Science*, 55: 244–252. DOI: <https://doi.org/10.1016/j.jas.2015.01.008>
- Locker, A** 2007 *In piscibus diversis*: the bone evidence for fish consumption in Roman Britain. *Britannia*, 38: 141–180. DOI: <https://doi.org/10.3815/000000007784016520>
- Locker, A** 2009 Fish Bone from Castle Mall (Site 777N). In: Albarella, U, Beech, M, Curl, J, Locker, A, Moreno García, M and Mulville, J (Eds.) *Norwich Castle: Excavations and Historical Survey, 1987–98 Part III: A Zooarchaeological Study*. East Anglian Archaeology. Dereham: Norfolk Museums and Archaeology Service, pp. 131–146.
- Locker, A** 2016 The decline in the consumption of stored cod and herring in post-medieval and early industrialised England: a change in food culture. In Barrett, J H and Orton, D C (Eds.) *Cod and Herring: the archaeology and history of medieval sea fishing*. Oxford: Oxbow, pp. 99–107.
- Lyman, R L** 2008 *Quantitative Paleozoology*. Cambridge University Press. DOI: <https://doi.org/10.1017/CBO9780511813863>
- McKechnie, I** and **Moss, M L** 2016 Meta-analysis in zooarchaeology expands perspectives on Indigenous fisheries of the Northwest Coast of North America. *Journal of Archaeological Science: Reports*, 8: 470–485. DOI: <https://doi.org/10.1016/j.jasrep.2016.04.006>
- Müldner, G** 2013 Stable isotopes and diet: their contribution to Romano-British research. *Antiquity*, 87(335): 137–149. DOI: <https://doi.org/10.1017/S0003598X00048675>
- Müldner, G** 2016 Marine fish consumption in medieval Britain: the isotope perspective from human remains. In: Barrett, J H and Orton, D C (Eds.) *Cod and Herring: the archaeology and history of medieval sea fishing*. Oxford: Oxbow, pp. 239–249.
- Orton, D C, Locker, A, Morris, J** and **Barrett J H** 2016 Fish for London. In: Barrett, J H and Orton, D C (Eds.) *Cod and Herring: the archaeology and history of medieval sea fishing*. Oxford: Oxbow, pp. 205–214.
- Orton, D C, Morris, J, Locker, A** and **Barrett, J H** 2014 Fish for the city: meta-analysis of archaeological cod remains and the growth of London's northern trade. *Antiquity*, 88(340): 516–530. DOI: <https://doi.org/10.1017/S0003598X00101152>
- Popper, V S** 1988 Selecting quantitative measurements in paleoethnobotany. In Hastorf, C A and Popper, V S (Eds.) *Current Paleoethnobotany: analytical methods and cultural interpretations of archaeological plant remains*. Chicago: University of Chicago Press, pp. 53–71.
- Porčić, M, Blagojević, T** and **Stefanović, S** 2016 Demography of the Early Neolithic population in central Balkans: population dynamics reconstruction using summed radiocarbon probability distributions. *PLoS ONE*, 11(8): e0160832. DOI: <https://doi.org/10.1371/journal.pone.0160832>
- Poulsen, R T** and **Holm, P** 2007 What can fisheries historians learn from marine science? The concept of catch per unit effort (CPUE). *International Journal of Maritime History*, 19(2): 89–112. DOI: <https://doi.org/10.1177/084387140701900205>
- Ratcliffe, J H** 2000 Aoristic analysis: the spatial interpretation of unspecific temporal events. *International Journal of Geographical Information Science*, 14(7): 669–679. DOI: <https://doi.org/10.1080/136588100424963>
- Rawcliffe, C** 2013 *Urban Bodies: communal health in late medieval English towns and cities*. Woodbridge: Boydell Press.
- R Core Team** 2015 *R: A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing. <http://www.R-project.org/>.
- Reynolds, R** 2016 The social complexities of early marine fish consumption: new evidence from southeast England. In: Barrett, J H and Orton, D C (Eds.) *Cod and Herring: the archaeology and history of medieval sea fishing*. Oxford: Oxbow, pp. 215–220.

- Roberts, C** 2007 *The Unnatural History of the Sea*. Washington: Island Press.
- Russell, N R, Twiss, K, Orton, D C and Demirergi, G A** 2013 More on the Çatalhöyük mammal remains. In: Hodder, I (Ed.) *Humans and Landscapes of Çatalhöyük: reports from the 2000–2008 seasons*. Los Angeles: Cotsen Institute, pp. 213–258.
- Serjeantson, D and Woolgar, C** 2006 Fish consumption in medieval England. In: Woolgar, C, Serjeantson, D and Waldron, T (eds.) *Food in Medieval England: diet and nutrition*. Oxford: Oxford University Press, pp. 102–130.
- Shennan, S, Downey, S S, Timpson, A, Edinborough, K, Colledge, S, Kerig, T, Manning, K and Thomas, M G** 2013 Regional population collapse followed initial agriculture booms in mid-Holocene Europe. *Nature Communications*, 4: 2486. DOI: <https://doi.org/10.1038/ncomms3486>
- Sinn, H-W** 1980 A rehabilitation of the Principle of Insufficient Reason. *Quarterly Journal of Economics*, 95(3): 493–506. DOI: <https://doi.org/10.2307/1884581>
- Surovell, T A and Brantingham, P J** 2007 A note on the use of temporal frequency distributions in studies of prehistoric demography. *Journal of Archaeological Science*, 34(11): 1868–1877. DOI: <https://doi.org/10.1016/j.jas.2007.01.003>
- Symonds, R S and Tomber R P** 1991 Late Roman London: an assessment of the ceramic evidence from the City of London. *Transactions of the London and Middlesex Archaeological Society*, 42: 59–99.
- Thomas, R** 2009 Bones of contention: why later post-medieval assemblages of animal bones matter. In: Horning, A and Palmer, M (Eds.) *Crossing Paths or Sharing Tracks: future directions in the archaeological study of post-1550 Britain and Ireland*. Woodbridge: Boydell and Brewer, pp. 133–148.
- Thomas, R, Holmes, M and Morris, J** 2013 “So bigge as bigge may be”: tracking size and shape change in domestic livestock in London (AD 1220–1900). *Journal of Archaeological Science*, 40(8): 3309–3325. DOI: <https://doi.org/10.1016/j.jas.2013.02.032>
- Timpson, A, Colledge, S, Crema, E, Edinborough, K, Kerig, T, Manning, K, Thomas, M G and Shennan, S** 2014 Reconstructing regional population fluctuations in the European Neolithic using radiocarbon dates: a new case-study using an improved method. *Journal of Archaeological Science*, 52: 549–557. DOI: <https://doi.org/10.1016/j.jas.2014.08.011>
- Van Neer, W and Ervynck, A** 2010 Defining “natural” fish communities for fishery management purposes: biological, historical and archaeological approaches. In: Bruce, S (Ed.) *Ecologies and Economies in Medieval and Early Modern Europe: studies in environmental history for Richard C Hoffmann*. Leiden: Brill, pp. 193–223. DOI: <https://doi.org/10.1163/ej.9789004180079.i-227.33>
- Van Neer, W and Ervynck A**, 2016 The rise of sea-fish consumption in inland Flanders. In: Barrett, J H and Orton, D C (Eds.) *Cod and Herring: the archaeology and history of medieval sea fishing*. Oxford: Oxbow, pp. 156–171.
- Wheeler, A and Jones, A K G** 1989 *Fishes*. Cambridge: Cambridge University Press.
- Williams, A N** 2012 The use of summed radiocarbon probability distributions in archaeology: a review of methods. *Journal of Archaeological Science*, 39(3): 578–589. DOI: <https://doi.org/10.1016/j.jas.2011.07.014>
- Wright, P J** 2010 Methodological issues in paleoethnobotany: a consideration of issues, methods, and cases. In: VanDerwarker, A M and Peres, T M (Eds.) *Integrating Zooarchaeology and Paleoethnobotany*. New York: Springer, pp. 37–64. DOI: [https://doi.org/10.1007/978-1-4419-0935-0\\_3](https://doi.org/10.1007/978-1-4419-0935-0_3)

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