Author Name: Sam Leggett

Affiliations:

Department of Archaeology, University of Cambridge, UK

School of Archaeology, University of Oxford, UK

School of History, Classics and Archaeology, University of Edinburgh, UK

Email: sal78@cantab.ac.uk; sam.leggett@arch.ox.ac.uk

ORCID: 0000-0001-6259-1457

Title: Tackling Western European Dietary Transitions in the First Millennium AD: a Hierarchical Meta-analytical Approach

Abstract:

Socio-environmental transitions during the first millennium AD had a wide-ranging impact across Europe which have interesting archaeological and palaeoecological implications. This paper uses published and new isotope data from across western Europe to look at changing resource use from c. 350-1200 AD. The geographical limits of millet and substantial marine consumption are identified; and comparisons between childhood and adult diets made across regions. It highlights cross-cultural interaction at a broad scale as well as focusing on these patterns within early medieval England as an in-depth regional case study. Doubt is cast onto the uptake of marine resource consumption in England following the Fish Event Horizon. However, changes to agricultural practices, the impact of Christianisation and the role of freshwater fish in diets are explored. By using a hierarchical meta-analytical approach, human-environment interactions are teased apart with significant implications for changing foodways in Europe during the first millennium AD.

Keywords: early medieval, isotopes, diet, identity, machine learning, foodways

Funding details: This work was supported by the Cambridge Trust and Newnham College through an international studentship (App No: 10386281); The Kathleen Hughes Memorial Fund; Cambridge Philosophical Society; and the University of Cambridge Fieldwork funding.

Biographical note: Sam Leggett completed her PhD at the University of Cambridge in 2020. She specialises in early medieval and biomolecular archaeology, and is interested in human-environment interactions, foodways, migration and cross-cultural contact in the first millennium AD.

Acknowledgements: I would like to thank my funders for supporting the research presented here. Thanks goes to my doctoral supervisors Susanne Hakenbeck and Tamsin O'Connell for their feedback on the chapter this originates from and their support through the PhD, to Catherine Hills for advice and feedback on an earlier version on this article, to Debby Banham for all of her advice on everything to do with Early Medieval food and drink, and to Emma Brownlee for her comments on earlier drafts. Thanks must also go to all the members of the Dorothy Garrod lab Cambridge past and present for their support over the years. I would also like to thank the three anonymous reviewers for their feedback on this article. Many thanks to the School of Archaeology at the University of Oxford for their support with a research associateship, where revisions to this article were undertaken.

Introduction

During the period of study (c. 350-1200 AD) there was considerable movement of people, ideas and goods, and cultural change (religious, economic, political etc.) throughout Europe. This is to greater and lesser extents visible in the archaeological record. This paper tackles issues of change and dynamism by studying the isotopic signatures of people buried in late Antique and early medieval cemeteries, to tell the story of socio-environmental interactions and transitions in the first millennium AD.

Everyone must eat and drink, and so in archaeology consumption is central to understanding the socio-economics of the past – not just what people ate, but how they obtained it, monetised it, thought about it, stored it, traded it, cooked it. It is a key part of everyday lived experiences (Jones, 2007; Wilson, 2006). Migrant groups often bring their foodways and other cultural traditions with them, and cross-cultural interaction can create new hybrid foods and identities (Cook, 2008; Vallianatos and Raine, 2008; Weller and Turkon, 2015).

Biomolecular archaeology gives us a unique toolkit for studying foodways, mobility, past bodies, and the context(s) in which these bodies lived. This toolkit can be applied at the individual and population scales, which makes it more versatile than other lines of archaeo-historical evidence. Isotopic analyses use the chemical memories of past events stored in the tissues of the dead to inform us about their lives. When these biochemical signatures are interpreted within archaeological frameworks, they help us better understand resource exploitation, agriculture, economy and ultimately foodways and identity.

This is the first integrated large-scale meta-analysis of collagen isotopic data for first millennium AD England and western Europe. There have been smaller and more focused assessments of isotopic data (e.g., O'Connell and Hull, 2011; Mays and Beavan, 2012; Hannah et al., 2018) but none at this scale. The aim was to contextualize England within contemporary Europe to better identify and assess the impact of major transitional events (i.e. agricultural changes, Christianisation and the 'Fish Event Horizon'); and to compare, contrast and quantify regional dietary variation for the period. England is the core focus here for two reasons. Firstly, it has the most isotopic data available of any region for c. 350-1200 AD. And secondly, it is arguably more

heavily impacted by the events noted above, making it an ideal case study to track these dietary transitions.

Basic Principles of Stable Isotope Analysis

The use of stable carbon and nitrogen isotopes for dietary reconstruction in archaeology is a well-established technique. This technique is dependent on the fact that different foods vary in their isotopic compositions and that these can be quantified (Gannes et al., 1998). Collagen reflects the average isotopic composition of dietary protein consumed during the period of tissue formation/turnover (Hedges et al., 2007). Bones form and remodel at different rates throughout life, whereas teeth, once formed, do not remodel; therefore, differential tissue selection gives varying isotopic snapshots through the life course.

Carbon stable isotope ratios can discern between diets based on C₃ plants and C₄ plants and are useful in differentiating between marine versus terrestrial food resources (O'Leary, 1988). Nitrogen stable isotope ratios indicate trophic level, and increase ~3-5‰ per level of the food chain. They are useful indicators of plant versus animal protein intake, as well as consumption of marine and freshwater resources when combined with carbon isotope values (Bocherens and Drucker, 2003; Lucy et al., 2009). $\delta^{15}\text{N}$ can also be altered by factors such as breastfeeding/weaning, pregnancy/lactation and periods of nutritional stress (Fuller et al., 2005; Beaumont et al., 2015).

The carbon in bioapatite (enamel, in this study) is derived from blood bicarbonate, which in turn derives from metabolism and is thought to represent whole diet (Ambrose and Norr, 1993; Tieszen and Fagre, 1993; Hedges, 2003; Zhu and Sealy, 2019). Enamel carbonate gives us a window into whole diet in childhood for the period of crown formation and mineralisation. This is a useful tool to combine with the largely protein-derived $\delta^{13}\text{C}$ values of collagen. Calculating the differences between enamel, bone and dentine can therefore narrow down trophic level and dietary changes through life.

First Millennium AD Dietary Transitions

This paper focuses on human-environment interactions. Specifically, how isotopic

signatures of past environments and human actions record these interactions, how major socio-environmental transitions may disrupt these patterns and if these transitions were widespread in western Europe. The events in question are significant socio-economic shifts which impacted foodways not only in England but across western Europe. They include the agricultural 'revolution' of the eighth to thirteenth centuries AD, Christianisation (seventh/eighth centuries in England), and the 'Fish Event Horizon' c. 1000 AD.

The re-introduction of Christianity to eastern England had political and economic implications. I am interested in how this may have affected diet, mainly through religious dietary laws such as those of Wihtred of Kent (c. 695 AD), which imposed fines on those eating meat during fasting (Whitelock, 1994). This allows us to investigate orthopraxy through the archaeological record (Lucy, 2000; Geake, 2002; Barrett, 2003; Dunn, 2010; Hannah et al., 2018; Knapp, 2018; Reynolds, 2015).

The 'agricultural revolution' between the eighth and thirteenth centuries AD saw an increase in cereal production, and changes to the types and quantities of crops ~~used~~ alongside technological innovations like the mouldboard plough which supported growing urban communities and facilitated changing power structures across most of Europe, but especially within England (Duby, 1997; Banham and Faith, 2014; Dyer et al., 2018; Hamerow et al., 2019, 2020).

Another key dietary shift is the 'Fish Event Horizon' (FEH) which is evident in the zooarchaeology of Europe around 1000 AD (Barrett et al., 2004a, 2004b). This marks a significant increase in marine fish consumption compared with earlier periods. Why there was an avoidance of marine resources before the ninth century is unclear, but it is likely a mixture of socio- environmental factors (Barrett et al., 2004a, 2004b, 2011; Serjeantson and Woolgar, 2006; Reynolds, 2015; Barrett, 2016; Orton et al., 2017). Such a major shift to marine resources should be evident in the human isotopic data as well as the zooarchaeological record, but has not been well-studied with a large human isotopic dataset (Müldner and Richards, 2007; Reynolds, 2015; Barrett, 2016; Müldner, 2016;).

These large-scale transitions and human adaptations to them demand a sub-

continental approach. This necessitated using meta-analytical methods in data collation and analysis. Computational meta-analyses are highly complex and an emerging style of research in archaeology (compared to psychology or clinical research where this approach is more common); they are ‘neither quick nor easy’ (Berman and Parker, 2002) due to the challenges of data standardisation, cross-study comparisons, and the statistical difficulties this poses (Greco et al., 2013; van Wely, 2014; Kruschke and Liddell, 2018). The following section briefly summarises the approach taken.

Materials and Methods

To date, no researchers have attempted a large-scale compilation of all the human isotopic data across western Europe for the first millennium AD at this scale. The dataset comprises of 5334 human isotopic entries, spanning 26 modern countries and 200 sites (see Figure 1). It is a subset of the entire dataset described in detail in Leggett *et al.* (2021), which also includes further bioapatite data not analysed here. Whilst the data used here are not comprehensive, with some geographical and chronological gaps, they do bring together the largest isotope dataset for first millennium AD western Europe, utilizing legacy data and newly generated isotopic data from England.

The regional designations in Figure 1 were created to avoid the anachronistic use of current political boundaries and the problematic use of ethnic identifiers for past geopolitical zones, whilst also incorporating some of the environmental and geological variation across Europe. This was done by plotting the sites to look for spatial clustering and adjusting these with $\delta^{18}\text{O}$ and $^{87}/^{86}\text{Sr}$ isoscapes (Evans et al., 2010, 2012, 2018; Bataille et al., 2018, 2020), as well as cultural factors such as grave good styles and linguistics (for full details see Leggett et al., 2021).

Figure 1: Map of sites drawn from Leggett et al. 2021 analysed in this paper, the tissues present and their geo-cultural/regional designations.

Statistical analyses were performed using Free and Open-Source R version 3.6.2 and Rstudio version 1.2.5033 (R Development Core Team, 2017; RStudio Team, 2019). The code and data are available here: <https://doi.org/10.17605/OSF.IO/6B8MZ>. Full data compilation and standardisation details are available in the companion data paper (Leggett et al., 2021) and further details on statistical analyses are available in the supplementary material.

Archaeological data often have large biases (e.g., large differences in sample sizes between groups), as is the case with these data. These biases would violate assumptions for common statistical approaches (e.g., ANOVA and student's t-tests) (Zuur et al., 2010). Sampling design was nested with varying levels of geographical designation (European Region, region within England, Environment type, site...), varying numbers of sexes, genders and age groups as well as funerary treatments and date categories represented across these locales. Given the nested nature of the data unsupervised machine learning (UML) in the form of hierarchical clustering was undertaken rather than using partitioning clustering methods which require user determination of the number of clusters in the dataset (e.g., k-means). Hierarchical

clustering was undertaken using Ward's hierarchical agglomerative clustering method and the Ward2 algorithm (Ward, 1963; Murtagh and Legendre, 2014; Kassambara, 2017). This was cross-validated by using 32 different indices (for details see supplementary material).

Hierarchical clustering was first visualised with a dendrogram showing the structure of the data and proximity of individuals to one another within this structure. Then the clusters were used to colour scatterplots for each tissue to better highlight the isotopic niches they represent. The clusters were also visualised as stacked bar plots to show the proportion of individuals in geo-cultural regions assigned to different clusters, and vice versa the proportion of individuals assigned to clusters buried in different geo-cultural regions.

BEST (Bayesian Estimation Supersedes the t-test) tests were used to compare between groups, these were run with R package "BEST" (Kruschke, 2013). For more details on the test, how it works and the test outputs from this analysis, see Kruschke (2013) and the supplementary material.

Chronological designations for individual burials were made on radiocarbon dates or numismatic evidence where available and based on established grave goods chronologies where these were absent (Bayliss et al., 2013; Brownlee, 2019; Leggett et al., 2021). However due to small sample sizes for regions outside England, chronological analyses were restricted to England only.

Bone and dentine data are analyzed separately below as very few individuals have isotopic data from both tissues, and so integrated clustering here would be of extremely limited utility. However, as dentine datasets grow this would be a logical next step.

Foodways and Diet in Europe during the First Millennium AD

Foodways and diets are isotopically characterised across western Europe to look at patterns at a broad scale. By comparing across and within regions we can look at dietary differences across the first millennium AD to investigate the impact of events like the FEH and determine their geographical origins and spread.

As outlined above, hierarchical cluster analysis was performed on both bone (n=4139) and dentine (n=931) collagen $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values at a western-European-wide scale.

Bone data

The data structure and isotopic ranges of the clusters can be seen in the dendrogram in Figure 2. Isotopic niches of the clusters are shown in Figure 3. Cluster 1 represents C_3 based diets with a range of trophic levels. Cluster 2.1 is distinguished by higher $\delta^{15}\text{N}_{\text{coll}}$ values. Bone cluster 2.2 is distinguished predominantly by its less negative $\delta^{13}\text{C}_{\text{coll}}$ values and with lower $\delta^{15}\text{N}_{\text{coll}}$ values compared to cluster 2.1.

Figure 2: Ward's method (1963) hierarchical clustering dendrogram of first millennium AD western European human bone $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}_{\text{coll}}$ stable isotope values (n=4139).

Figure 3: Scatterplot of $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ from first millennium AD western European human bone coloured by cluster number determined by analyses from Figure 2.

A north-south gradient in diets across western Europe is clear in Figures 4 and 5. The dominance of certain regions and areas within these clusters may be useful for human provenancing by foodways, and suggest where some of these foodways, marine food consumption in particular originated from.

England dominates cluster 1 due to its large sample size (1899/2917 in that cluster). Cluster 1 is particularly dominant in 'Germanic' areas of continental Europe, and Britain and Ireland. The North Atlantic islands and Greece have over 50% of individuals assigned to cluster 1 showing the dominance of C_3 diets in these regions.

Cluster 2.1 indicates higher trophic positions (and therefore includes some possible marine consuming individuals). Figure 4 highlights the Scandinavian and Baltic dominance of this cluster, which supports a cultural genesis of the FEH in Scandinavia (Barrett et al., 2004a; Barrett and Richards, 2004; Barrett, 2016). This cluster is the most dominant in Atlantic and Arctic Norway, the Baltic, and Scotland and the Scottish Islands but not present in high numbers elsewhere. The lack of cluster 2.1 elsewhere is likely due to a lack of access to marine resources inland. However, many of the individuals in cluster 2.1 have bone $\delta^{13}C_{coll}$ values below -18.5‰, and date to the seventh century onwards. So, perhaps this is better interpreted as more generalized

nitrogen enrichment watershed, and not solely a marine based transition. Cluster 2.1 with its higher $\delta^{15}\text{N}_{\text{coll}}$ bone values cannot support a particularly ubiquitous marine-based FEH across Europe, but instead may show increased meat consumption more broadly, and possibly even a FEH with a greater freshwater component which is supported by the enamel $\delta^{13}\text{C}_{\text{carb}}$ values.

Figure 4: Proportion of individuals in each bone $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}_{\text{coll}}$ cluster coloured by region.

Figure 5: Proportion of individuals in each region coloured by $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}_{\text{coll}}$ bone cluster, using the same colour scheme as Figure 2 and Figure 3.

Cluster 2.2 is dominant in, and dominated by, the Mediterranean and parts of central and eastern Europe. The reasons for this are three-fold. Firstly, it shows the regionally distinctive consumption of millet and other C₄ crops introduced from the Eurasian steppe (Lightfoot et al., 2015; Hakenbeck et al., 2017; Amorim et al., 2018; Vidal-Ronchas et al., 2019; Filipović et al., 2020). Secondly, it shows interactions across the Mediterranean into Africa and the introduction of C₄ plants through Iberia and the Balearic Islands, likely via late Roman and Islamic Caliphate influences (López-Costas and Müldner, 2016; Alaica et al., 2019; Alexander et al., 2019; Dury et al., 2019; García-Collado et al., 2019; Guede et al., 2017; Jordana et al., 2019). Thirdly, it represents individuals who are exploiting lower trophic level marine resources or eating smaller proportions of marine resources in their diets compared with those in cluster 2.1 (Bourbou and Richards, 2007; Bourbou et al., 2011; Dury et al., 2019).

The geographical boundaries for 50% or less inclusion of clusters 2.1 and 2.2 are in Scotland and the Scottish Isles, and Austro-Hungary and Bavaria respectively. These resource or foodways boundaries match with historical and archaeological evidence which show these regions to be key points of contact with the Viking and Steppe groups who are credited with introducing the FEH and millet cultivation respectively (Barrett et al., 2004a; Barrett and Richards, 2004; Richards et al., 2006; Hakenbeck et al., 2017; Amorim et al., 2018; Vidal-Ronchas et al., 2019; Filipović et al., 2020).

There are some exceptions to these spheres of influence and the north-south gradient. First is the lack of marine consumption in the North Atlantic, which appears to be due to more terrestrial and freshwater resources being consumed as determined by sulphur stable isotope analysis (Sayle et al., 2016). The second is the <40% proportion of individuals in Greece in cluster 2.2. Byzantine Greek diets show little to no influence of central Asian millet consumption, but instead are more terrestrially C₃ and low-trophic marine resource-based (Bourbou and Richards, 2007; Bourbou et al., 2011). Croatia is the only region to be entirely dominated by one dietary cluster (2.2). The algorithm included many of the individuals from Croatia with signatures more consistent with C₃ diets in cluster 2.2, perhaps reflecting tight similarities in this and neighbouring populations, reflecting mixing of C₃/C₄ consumption in the region, and the restricted sample

Hierarchical clustering of bone isotopic values in the core focus –England – confirms the dominance of foods from C₃ ecosystems. England's cluster profile in Figure 5 is most like the Skagerrak-Kattegat-Jutland Basin, Frisia and Saxony, and Normandy/Neustria. These regions are some of its nearest neighbours with climatic and environmental similarities. These three regions are areas with historically and isotopically attested migration into England during our period. They also have known migration into these regions from Norway, Sweden and the Baltic. Therefore, given environmental similarities and migrant histories, these dietary profiles make sense. Furthermore, when individuals assigned to clusters 2.1 and 2.2 are investigated in the database, the Fennoscandian and Baltic routes of these minority diets are even clearer.

Cluster 2.1 individuals in England mostly date to the eighth century onwards and are buried in cemeteries with known or suspected Scandinavian migrants (e.g., St John's College Oxford and York), or strong Christian ties (i.e., monasteries or churchyard cemeteries, e.g., Caister-by-Yarmouth and Raunds Furnells). These individuals represent a dual aspect to this FEH in England – introduced Scandinavian marine consumption and Christian foodways substituting fish and fowl for other meats.

Individuals in cluster 2.2 in England are slightly more complex in their interpretation but are predominantly from cemeteries which span the third to fifth centuries AD and are therefore late-Roman, and as such represent markedly different foodways compared to early medieval sites. 22 of the 69 individuals assigned to cluster 2.2 date to the later part of our period, spanning the seventh to thirteenth centuries. Most are from churchyard cemeteries in Norwich, and the Viking mass grave at Repton (Bayliss et al., 2009; Jarman et al., 2018). Due to chronology and context these individuals are therefore placed into the category of marine consumers who are at a lower trophic position compared to those in cluster 2.1, who might also have a high proportion of C₃ resources in their diets, which reflects both Scandinavian and Christian foodways.

Dentine data

The same process was applied to human dentine values to compare these signatures from childhood and earlier life diets with those for bone above. The dendrogram structure and isotopic ranges of clusters for dentine are very similar to that for bone

above, with two major branches (Figure 6). This is then visualised as a scatterplot in Figure 7.

Figure 6: Ward's method (1963) hierarchical clustering dendrogram of first millennium AD western European human dentine stable isotope values –with $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ from the same individuals ($n=931$).

Figure 7: Scatterplot of $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ from first millennium AD western European human dentine coloured by cluster number determined by analyses from Figure 6.

Dentine cluster 1 is the largest with n=552. It corresponds with bone cluster 1 and represents C₃ based diets across several trophic levels. Dentine cluster 2.1 roughly equates to bone cluster 2.2, and likewise has the smallest sample size with n=34. Dentine cluster 2.1 is assumed here to represent C₄/marine based diets with a similar range in $\delta^{15}\text{N}_{\text{coll}}$ values to cluster 1. Cluster 2.2 therefore is differentiated by its higher $\delta^{15}\text{N}_{\text{coll}}$ values compared to the other two groups and equates to bone cluster 2.1. As with bone, individuals in this higher trophic level group appear to be mostly C₃ terrestrial or freshwater protein consumers, although a small number do have $\delta^{13}\text{C}_{\text{coll}}$ values which overlap of those in cluster 2.1 and could therefore be consuming a higher proportion of marine resources or animals fed on C₄ plants to those in cluster 2.1 and could have been consuming mixed terrestrial/marine diets (see carbonate discussion below).

Figure 8: Proportion of individuals in each dentine $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}_{\text{coll}}$ cluster coloured by region.

Figure 9: Proportion of individuals in each region coloured by $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ dentine cluster, using the same colour scheme Figure 6 and Figure 7.

Region make-up of the clusters and proportions of clusters are shown above in Figure 8 and Figure 9. The dominance of England in the dataset is clear. Due to the reduced number of regions represented in the dentine data, regional diversity in clusters is not as high as in bone. Despite this, the above findings from bone are supported by the dentine data, with this pattern of a dietary gradient running north-south/northwest-southeast across Europe in both datasets.

Cluster 1 as the C₃ terrestrial/freshwater consuming cluster, whilst dominated by England, is found in every region. The regions with the highest proportions of this cluster are the Po Valley, the Skagerrak-Kattegat-Jutland Basin and England.

Cluster 2.1 is made up almost entirely of individuals buried in Croatia, with a handful of entries from the Po Valley and the Baltic. This shows a clear difference between the dentine and bone from the Po Valley which suggests a change from a more C₃ based diet in childhood to more C₄ resources later in life. The Baltic is the only region with all three clusters present, which mirrors its isotopic variability for both bone (above) and enamel (see below). However, one individual assigned dentine cluster 2.1 in the Baltic is an outlier for the region and site (Triberga (Howcroft et al., 2012)), and could represent a migrant from one of the C₄ consuming regions discussed here, or further

afield.

As mentioned above cluster 2.2 is predominantly (255/345) individuals from England, with the rest coming from Scotland and the Scottish Isles, the Skagerrak-Kattegat-Jutland Basin, Atlantic and Arctic Norway, and the Baltic. The proportions of this cluster in each of these regions mirrors the trend seen above for bone, with higher proportions of people with ^{15}N enrichment found in Atlantic and Arctic Norway, and the Baltic. England and the Skagerrak-Kattegat-Jutland Basin again closely resemble each other in cluster proportions. Individuals in England assigned to dentine cluster 2.2 are (again) predominantly later churchyard burials (e.g., Black Gate Newcastle or Raunds Furnells) or from sites with known Viking links (Ridgeway Hill, Weymouth). There are six earlier individuals dating to the sixth-eighth centuries AD. These burials are outliers for their cemeteries in this cluster assignment, and this could perhaps suggest they were migrants as all are older adults bar one child from Southam, and post-weaning teeth were used.

Breastfeeding and weaning practices could play a role in these signatures (Fuller et al., 2006; Haydock et al., 2013), although the similarities in values and the large-scale geographical patterns seen above suggest this has minimal impact on the overall results. For most regions childhood and adult diets were very similar as shown here.

Diachronic Change within England

To test the cause(s) for the isotopic variability found above, the data for England has been assessed chronologically. Looking at the data through time will allow us to see if any changes in diet align with any of the first millennium transitions described above.

Figure 10-c shows a great deal of overlap between diets in England across the three chronological phases, but with noticeable changes in $\delta^{15}\text{N}$ values. It is tempting to equate the change seen for c. 790-1066 AD+ as evidence for the FEH however by looking at changes in $\delta^{13}\text{C}_{\text{coll}}$ (Figure 10-a) and $\delta^{15}\text{N}_{\text{coll}}$ (Figure 10-b) values separately this interpretation unravels.

Figure 10: Bone collagen $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from England through time– A) $\delta^{13}\text{C}_{\text{coll}}$ values, B) $\delta^{15}\text{N}_{\text{coll}}$ values, C) bag plots of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values and D) bag plots of $\Delta^{13}\text{C}_{\text{enamel-dentine}}$ and $\delta^{13}\text{C}_{\text{carb}}$. For plots A, B and C $n=187$ for Roman (purple), $n=1603$ for c. fourth-to-eighth century (teal) and $n=229$ for the late-eighth-to-thirteenth century (yellow). For D $n=176$ and $n=34$ for teal and yellow respectively.

There is a dietary shift from the Roman period to the beginning of the Early Middle Ages evident in both $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}_{\text{coll}}$ values, with a drop in $\delta^{13}\text{C}_{\text{coll}}$ values at the end of the Roman period. Whilst not the main focus here it is interesting and may reflect a whole host of culinary and economic changes in Britain after the end of the western Roman Empire (Rizzetto et al., 2017). The high degree of overlap between the Roman and post-Roman bags and loops (as seen in Figure 10c and d) does support theories for a high degree of dietary continuity (in terms of isotopic signatures) between the two periods (Banham and Faith, 2014; Sakai, 2017). This shift is supported by a BEST test but equates to a difference in posterior predictive means of 0.73‰ which is not large. However, the strong peak and overall shift in distribution to more negative $\delta^{13}\text{C}_{\text{coll}}$ values add more weight to the argument of an increase in freshwater consumption and agricultural changes during the Early Middle Ages.

The differences in distribution shape and range show more variety in bone $\delta^{13}\text{C}_{\text{coll}}$ values for the later period. There is a C_3 diet of both terrestrial and freshwater resources with no substantial or widespread marine consumption in adulthood. The

bone $\delta^{15}\text{N}_{\text{coll}}$ data in Figure 10-b has increasing means, maximum values and more positively shifted distributions over time. The BEST tests between periods for bone $\delta^{15}\text{N}_{\text{coll}}$ indicate that these differences are real, although the shifts are small, around +1‰ in mean per period. This aligns with changes seen in zooarchaeological, isotopic and burial data from Kent, where changing dietary practices in line with Christianisation and changing worldviews on death and the afterlife have been suggested (Reynolds, 2015; Knapp, 2018; Brownlee, 2021; Leggett, 2021). The clear spike in bone $\delta^{15}\text{N}_{\text{coll}}$ values from the eighth century onwards is not accompanied by the necessary increase in $\delta^{13}\text{C}_{\text{coll}}$ to support a marine FEH in England close to the year 1000 AD as previously argued (Barrett et al., 2004a, 2004b; Barrett, 2016; Müldner, 2016; Orton et al., 2017). However, nitrogen enrichment with stable carbon isotopic values in post-Roman England instead supports other dietary transitions such as increased freshwater/terrestrial protein, or agricultural innovations which would increase $\delta^{15}\text{N}$ values in cereal crops such as those seen in the archaeobotanical isotopic evidence from Stafford (Hamerow et al., 2020). The (early) medieval crop isotope data from Stafford show ^{15}N enrichment in all crops (barley, oats, wheat, and rye) through time, with wheat becoming less enriched in ^{13}C in the eleventh-to-thirteenth centuries, and other crop $\delta^{13}\text{C}$ values remaining mostly stable with some decrease in values. Alongside the other weed ecology and pollen data, the investigators believe this change is due to extensification and adoption of the mouldboard plough, allowing for more nitrogen-rich soils to be cultivated, and not manuring; and that these isotope values were likely to be passed onto consumers as I propose here (Hamerow et al., 2020).

To investigate these possibilities $\Delta^{13}\text{C}_{\text{enamel-dentine}}$ values were used to infer trophic level and protein source. We would expect to see values in consumer tissues increasing with decreasing dietary protein (i.e., larger in herbivores, smaller in carnivores) (Clementz et al., 2009). $\Delta^{13}\text{C}_{\text{bioapatite-collagen}}$ values below 4‰ are expected for individuals whose dietary protein was almost entirely derived from aquatic (freshwater or marine) sources given the data from ecological models and humans from Jomon Japan (Clementz and Koch, 2001; Clementz et al., 2007, 2009; Kusaka et al., 2015). Figure 10-d highlights that for the small proportion of individuals in the period c. 790-1066+ AD with higher trophic levels ($\Delta^{13}\text{C}_{\text{enamel-dentine}}$ values ~ 4 ‰), their $\delta^{13}\text{C}_{\text{carb}}$ values indicate this trophic position could be due to ^{13}C depletion in freshwater organism lipids (Robson et al., 2016; Taylor et al., 2017; Guiry, 2019). This would impact $\delta^{13}\text{C}_{\text{carb}}$ values

over $\delta^{13}\text{C}_{\text{coll}}$ in consumers due to the differential dietary routing explained above. This is the same for the earlier period as well with a strong trend for both broad time periods. There is a high degree of overlap between both periods with a high degree of variability in diets c.350-790AD which is not as clear in Figure 10-b and -c where chronological change from c.790 AD is more apparent.

Whilst I agree with Müldner (2016) that there is no evidence for any large-scale marine consumption in the post-Roman/pre-Viking periods, I go further and suggest that, aside from a few outlying individuals with some tenuous marine dietary signatures, there is no evidence for the FEH in England up to the eleventh century using these multi-tissue analyses. For bone entries, 119 out of 2023 $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signatures in England are classified by UML as bone cluster 2.1 or 2.2 (marine/ C_4 diets). 49 of these are late-Roman, and a further 23 are juveniles from Raunds Furnells, and probably represent osteological paradox (physiological stress leading to their untimely deaths which is known to alter isotopic values) and breastfeeding signals rather than marine consumption (Fuller et al., 2005; Beaumont et al., 2015; DeWitte and Stojanowski, 2015). Many of the remaining 47 in cluster 2.1/2.2 have strong Scandinavian ties and are assumed migrants (Ketton Quarry, Repton, St John's College Oxford) and so these signatures seem to be largely imported and not endogenous to England. For the 50 individuals with bone $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values firmly dating to 1000-1400 AD strong marine dietary signatures are not the norm (only five individuals from York dating to c. 1050-1200AD are categorised as having cluster 2.1 bone signatures – see Leggett *et al.* (2021)), but more post-1000 AD samples are needed. What has been key to this is using multi-isotope and multi-tissue evidence in various combinations and using these to create tissue offsets and enrichment factors which can better assess trophic levels and show freshwater resource consumption without the use of sulphur, as well as UML to classify dietary signatures *a priori*.

When we use traditional biplots, bagplots or even separate out the tissue by element, it is easy to make convincing arguments for the FEH in England. However, the lack of a marked increase in bone $\delta^{13}\text{C}$ through time, and tissue enrichment factors alongside enamel carbonate indicates that this shift in $\delta^{15}\text{N}_{\text{coll}}$ values post-790AD is not in fact a marine FEH. There is clear isotopic evidence for freshwater resource consumption which matches fish bone assemblages from London where catch per unit increases in

the seventh century AD (Orton et al., 2017). However, zooarchaeological evidence for both freshwater and marine species spikes considerably around 1000AD in London, and other parts of Britain, which is not fully supported by the human isotopic evidence here (Barrett et al., 2004a; Barrett and Richards, 2004; Serjeantson and Woolgar, 2006; Reynolds, 2015; Orton et al., 2017).

How can we reconcile this evidence? There is evidence for freshwater consumption, more so in c.350-790AD, and a significant number of individuals in both parts of the (early) Medieval period with low trophic enrichment factors. What could be causing the mismatch between high $\delta^{15}\text{N}_{\text{coll}}$ values (from either tissue) above $\sim 8\text{‰}$, which and 'herbivorous' $\Delta^{13}\text{C}_{\text{enamel-dentine}}$ values in some individuals? One possible explanation comes from Stafford, mentioned above. Extensification practices causing crop ^{15}N enrichment, with minor ^{13}C depletion, getting passed onto human consumers could cause the patterns seen here. Although human, wild herbivore and plant isotopes from the same site would be needed to explore this hypothesis further. If the increased demand for marine fish seen in the zooarchaeological evidence made up $<20\%$ of whole diets, it would be isotopically and metabolically swamped by these terrestrial/freshwater signatures and so is invisible in the collagen signatures presented here. Therefore, this may point to a more plant-based explanation for changes in diet across the period.

Conclusions

This approach to categorising human isotopic niches highlights the need for multi-tissue studies when interested in diet; and the interesting outcomes from using unsupervised machine learning methods showcases the need to reconsider how statistics are used in archaeological stable isotope studies. Whilst some of the trends here may seem intuitive, UML allows isotopic data users to explore clustering *a priori*, removing user determination. This is important to avoid biasing cluster construction, to ensure more robust backing for our subsequent archaeological interpretations of cluster patterning.

The clear north-south gradient of dietary signals in both bone and dentine found across Europe is evidence for more marine based diets in Scandinavia being introduced further south through settlement, and the gradual penetration of C_4 crops and migrants

with substantial C₄ diets from the east. However, the majority of western Europe consumed C₃ based diets in both childhood and adulthood. Nitrogen enrichment over time in England cannot be linked directly to the 'Fish Event Horizon' but instead diachronic change supports changing foodways influenced by Christian orthopraxy and the agricultural revolution of the eighth-thirteenth centuries. Shifts in foodways during the period reflect changes in economics and agriculture but also changing worldviews (e.g., Christianisation). These were complex societies in persistent cross-cultural contact who were part of large sub-continental networks which influenced the changes we see in material culture, foodways and thought, throughout the period.

References

- Alaica AK, Schalburg-Clayton J, Dalton A, et al. (2019) Variability along the frontier: stable carbon and nitrogen isotope ratio analysis of human remains from the Late Roman–Early Byzantine cemetery site of Joan Planells, Ibiza, Spain. *Archaeological and Anthropological Sciences* 11(8): 3783–3796. DOI:10.1007/s12520-018-0656-0.
- Alexander MM, Gutiérrez A, Millard AR, et al. (2019) Economic and socio-cultural consequences of changing political rule on human and faunal diets in medieval Valencia (c. fifth–fifteenth century AD) as evidenced by stable isotopes. *Archaeological and Anthropological Sciences*. DOI: 10.1007/s12520-019-00810-x.
- Ambrose SH and Norr L (1993) Experimental Evidence for the Relationship of the Carbon Isotope Ratios of Whole Diet and Dietary Protein to Those of Bone Collagen and Carbonate. In: Lambert JB and Grupe G (eds) *Prehistoric Human Bone*. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 1–37. DOI: 10.1007/978-3-662-02894-0_1.
- Amorim CEG, Vai S, Posth C, et al. (2018) Understanding 6th-century barbarian social organization and migration through paleogenomics. *Nature Communications* 9(1): 1–11. DOI: 10.1038/s41467-018-06024-4.
- Banham D and Faith R (2014) Continuities and changes in arable husbandry. In: *Anglo-Saxon Farms and Farming*. Oxford: Oxford University Press, pp. 269–292. DOI: 10.1093/acprof:oso/9780199207947.001.0001.
- Barrett JH (2003) Christian and Pagan Practice during the Conversion of Viking Age Orkney and Shetland. In: Carver MOH (ed.) *The Cross Goes North: Processes of Conversion in Northern Europe, AD 300-1300*. Woodbridge, Suffolk, UK & Rochester, NY: York Medieval Press; Boydell & Brewer, pp. 207–227.
- Barrett JH (2016) Medieval Sea Fishing, AD 500-1550: Chronology, Causes and Consequences. In: Barrett JH and Orton DC (eds) *Cod and Herring: The Archaeology and History of Medieval Sea Fishing*. Oxford: Oxbow Books, pp. 250–272.

- Barrett JH and Richards MP (2004) Identity, Gender, Religion and Economy: New Isotope and Radiocarbon Evidence for Marine Resource Intensification in Early Historic Orkney, Scotland, UK. *European Journal of Archaeology* 7(3): 249–271. DOI: 10.1177/1461957104056502.
- Barrett JH, Locker AM and Roberts CM (2004a) 'Dark Age Economics' revisited: the English fish bone evidence AD 600–1600. *Antiquity* 78(301): 618–636. DOI: 10.1017/S0003598X00113262.
- Barrett JH, Locker AM and Roberts CM (2004b) The origins of intensive marine fishing in medieval Europe: the English evidence. *Proceedings of the Royal Society of London. Series B: Biological Sciences* 271(1556): 2417–2421. DOI: 10.1098/rspb.2004.2885.
- Barrett JH, Orton D, Johnstone C, et al. (2011) Interpreting the expansion of sea fishing in medieval Europe using stable isotope analysis of archaeological cod bones. *Journal of Archaeological Science* 38(7): 1516–1524. DOI: 10.1016/j.jas.2011.02.017.
- Bataille CP, Holstein ICC von, Laffoon JE, et al. (2018) A bioavailable strontium isoscape for Western Europe: A machine learning approach. *PLOS ONE* 13(5): e0197386. DOI: 10.1371/journal.pone.0197386.
- Bataille CP, Crowley BE, Wooller MJ, et al. (2020) Advances in global bioavailable strontium isoscapes. *Palaeogeography, Palaeoclimatology, Palaeoecology*: 109849. DOI: 10.1016/j.palaeo.2020.109849.
- Bayliss A, Shepherd Popescu E, Cook G, et al. (2009) Radiocarbon Dating. In: *Norwich Castle: Excavations and Historical Survey 1987–98. Part I Anglo-Saxon to c.1345*. East Anglian Archaeology 132. Gressenhall: NAU Archaeology and Norfolk Historic Environment, pp. 237–253.
- Bayliss A, Scull C, McCormac G, et al. (2013) *Anglo-Saxon Graves and Grave Goods of the 6th and 7th Centuries AD: A Chronological Framework* (eds J Hines and Alex Bayliss). The Society for Medieval Archaeology monograph 33. London: Society for Medieval Archaeology.
- Beaumont J, Montgomery J, Buckberry J, et al. (2015) Infant mortality and isotopic complexity: New approaches to stress, maternal health, and weaning. *American Journal of Physical Anthropology* 157(3): 441–457. DOI: 10.1002/ajpa.22736.
- Berman NG and Parker RA (2002) Meta-analysis: Neither quick nor easy. *BMC Medical Research Methodology* 2: 10. DOI: 10.1186/1471-2288-2-10.
- Bocherens H and Drucker D (2003) Trophic level isotopic enrichment of carbon and nitrogen in bone collagen: case studies from recent and ancient terrestrial ecosystems. *International Journal of Osteoarchaeology* 13(1–2): 46–53. DOI: 10.1002/oa.662.
- Bourbou C and Richards MP (2007) The Middle Byzantine menu: palaeodietary information from isotopic analysis of humans and fauna from Kastella, Crete. *International Journal of Osteoarchaeology* 17(1): 63–72. DOI: 10.1002/oa.855.

- Bourbou C, Fuller BT, Garvie-Lok SJ, et al. (2011) Reconstructing the diets of Greek Byzantine populations (6th-15th centuries AD) using carbon and nitrogen stableisotope ratios. *American Journal of Physical Anthropology* 146(4): 569–581. DOI: 10.1002/ajpa.21601.
- Brownlee E (2021) Connectivity and funerary change in early medieval Europe. *Antiquity* 95(379): 142–159. DOI:10.15184/aqy.2020.153.
- Brownlee EC (2019) *Burial Practices in Transition: A study of the social, cultural and religious cohesion of early medieval Europe*. PhD. University of Cambridge, Cambridge.
- Clementz MT and Koch PL (2001) Differentiating aquatic mammal habitat and foragingecology with stable isotopes in tooth enamel. *Oecologia* 129(3): 461–472. DOI: 10.1007/s004420100745.
- Clementz MT, Koch PL and Beck CA (2007) Diet induced differences in carbon isotope fractionation between sirenians and terrestrial ungulates. *Marine Biology* 151(5): 1773–1784. DOI: 10.1007/s00227-007-0616-1.
- Clementz MT, Fox-Dobbs K, Wheatley PV, et al. (2009) Revisiting old bones: coupled carbon isotope analysis of bioapatite and collagen as an ecological and palaeoecological tool. *Geological Journal* 44(5): 605–620. DOI: 10.1002/gj.1173.
- Cook I (2008) Geographies of food: mixing. *Progress in Human Geography* 32(6): 821–833. DOI: 10.1177/0309132508090979.
- DeWitte SN, and Stojanowski CM (2015). The Osteological Paradox 20 Years Later: Past Perspectives, Future Directions. *Journal of Archaeological Research* 23(4): 397–450. <https://doi.org/10.1007/s10814-015-9084-1>.
- Duby G (1997) La révolution agricole médiévale: Discussion. *Études rurales* (145/146). EHESS: 51–57.
- Dunn M (2010) *The Christianization of the Anglo-Saxons c.597-c.700: Discourses of Life, Death and Afterlife*. London: Continuum.
- Dury G, Lythe A, Marquez-Grant N, et al. (2019) The Islamic cemetery at 33 Bartomeu Vicent Ramon, Ibiza: investigating diet and mobility through light stable isotopesin bone collagen and tooth enamel. *Archaeological and Anthropological Sciences* 11(8): 3913–3930. DOI: 10.1007/s12520-018-0644-4.
- Dyer C, Thoen E and Williamson T (2018) Conclusion: the rationale of open fields. In: *Peasants and Their Fields*. Comparative Rural History of the North Sea Area 16. Brepols Publishers, pp. 257–275. DOI: 10.1484/M.CORN-EB.5.114276.
- Evans J, Chenery C, Mee K, et al. (2018) Biosphere Isotope Domains GB (V1): Interactive Website. *British Geological Survey*. DOI: 10.5285/3b141dce-76fc-4c54-96fa-c232e98010ea.
- Evans JA, Montgomery J, Wildman G, et al. (2010) Spatial variations in biosphere⁸⁷Sr/⁸⁶Sr in Britain. *Journal of the Geological Society* 167(1): 1–4. DOI: 10.1144/0016-76492009-090.

- Evans JA, Chenery CA and Montgomery J (2012) A summary of strontium and oxygen isotope variation in archaeological human tooth enamel excavated from Britain. *Journal of Analytical Atomic Spectrometry* 27(5): 754–764. DOI: 10.1039/c2ja10362a.
- Filipović, D, Meadows J, Dal Corso M, Kirleis W, Alsleben A, Akeret Ö, Bittmann F, et al. (2020) New AMS 14C Dates Track the Arrival and Spread of Broomcorn Millet Cultivation and Agricultural Change in Prehistoric Europe. *Scientific Reports* 10(1): 13698. <https://doi.org/10.1038/s41598-020-70495-z>.
- Fuller BT, Fuller JL, Sage NE, et al. (2005) Nitrogen balance and $\delta^{15}\text{N}$: why you're not what you eat during nutritional stress. *Rapid Communications in Mass Spectrometry* 19(18): 2497–2506. DOI: 10.1002/rcm.2090.
- Fuller BT, Molleson TI, Harris DA, et al. (2006) Isotopic Evidence for Breastfeeding and Possible Adult Dietary Differences from Late/Sub-Roman Britain. *American Journal of Physical Anthropology* 129(1): 45–54. DOI: 10.1002/ajpa.20244.
- Gannes LZ, del Rio CM and Koch P (1998) Natural Abundance Variations in Stable Isotopes and their Potential Uses in Animal Physiological Ecology. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology* 119(3): 725–737. DOI: 10.1016/S1095-6433(98)01016-2.
- García-Collado MI, Ricci P, Catalán Ramos R, et al. (2019) Palaeodietary reconstruction as an alternative approach to poorly preserved early medieval human bone assemblages: the case of Boadilla (Toledo, Spain). *Archaeological and Anthropological Sciences* 11(8): 3765–3782. DOI: 10.1007/s12520-018-0672-0.
- Geake H (2002) Persistent Problems in the Study of Conversion-Period Burial in England. In: Lucy S and Reynolds A (eds) *Burial in Early Medieval England and Wales*. No. 17. London, UK: The Society for Medieval Archaeology.
- Greco T, Zangrillo A, Biondi-Zoccai G, et al. (2013) Meta-analysis: pitfalls and hints. *Heart, Lung and Vessels* 5(4): 219–225.
- Guede I, Ortega LA, Zuluaga MC, et al. (2017) Isotope analyses to explore diet and mobility in a medieval Muslim population at Tauste (NE Spain). *PLOS ONE* 12(5): e0176572. DOI: 10.1371/journal.pone.0176572.
- Guiry E (2019) Complexities of Stable Carbon and Nitrogen Isotope Biogeochemistry in Ancient Freshwater Ecosystems: Implications for the Study of Past Subsistence and Environmental Change." *Frontiers in Ecology and Evolution* 7. <https://doi.org/10.3389/fevo.2019.00313>.
- Hakenbeck SE, Evans J, Chapman H, et al. (2017) Practising pastoralism in an agricultural environment: An isotopic analysis of the impact of the Hunnic incursions on Pannonian populations. *PLOS ONE* Caramelli D (ed.) 12(3): e0173079. DOI: 10.1371/journal.pone.0173079.
- Hamerow H, Bogaard A, Charles M, et al. (2019) Feeding Anglo-Saxon England: the bioarchaeology of an agricultural revolution. *Antiquity* 93(368): e12. DOI: 10.15184/aqy.2019.27.

- Hamerow H, Bogaard A, Charles M, et al. (2020) An Integrated Bioarchaeological Approach to the Medieval 'Agricultural Revolution': A Case Study from Stafford, England, c.ad 800–1200. *European Journal of Archaeology*: 1–25. DOI: 10.1017/ea.2020.6.
- Hannah EL, McLaughlin TR, Keaveney EM, et al. (2018) Anglo-Saxon diet in the Conversion period: A comparative isotopic study using carbon and nitrogen. *Journal of Archaeological Science: Reports* 19: 24–34. DOI: 10.1016/j.jasrep.2018.02.012.
- Haydock H, Clarke L, Craig-Atkins E, et al. (2013) Weaning at Anglo-Saxon Raunds: Implications for changing breastfeeding practice in Britain over two millennia: Weaning at Anglo-Saxon Raunds. *American Journal of Physical Anthropology* 151(4): 604–612. DOI: 10.1002/ajpa.22316.
- Hedges REM (2003) On bone collagen–apatite-carbonate isotopic relationships. *International Journal of Osteoarchaeology* 13(1–2): 66–79. DOI: 10.1002/oa.660.
- Hedges REM, Clement JG, Thomas CDL, et al. (2007) Collagen turnover in the adult femoral mid-shaft: Modeled from anthropogenic radiocarbon tracer measurements. *American Journal of Physical Anthropology* 133(2): 808–816. DOI: 10.1002/ajpa.20598.
- Howcroft R, Eriksson G and Lidén K (2012) Conformity in Diversity? Isotopic investigations of infant feeding practices in two iron age populations from Southern Öland, Sweden. *American Journal of Physical Anthropology* 149(2): 217–230. DOI: 10.1002/ajpa.22113.
- Jarman CL, Biddle M, Higham T, et al. (2018) The Viking Great Army in England: new dates from the Repton charnel. *Antiquity* 92(361): 183–199. DOI: 10.15184/aqy.2017.196.
- Jones M (2007) *Feast: Why Humans Share Food*. Oxford: Oxford University Press.
- Jordana X, Malgosa A, Casté B, et al. (2019) Lost in transition: the dietary shifts from Late Antiquity to the Early Middle Ages in the North Eastern Iberian Peninsula. *Archaeological and Anthropological Sciences* 11(8): 3751–3763. DOI: 10.1007/s12520-019-00777-9.
- Kassambara A (2017) *Practical Guide to Cluster Analysis in R: Unsupervised Machine Learning: Volume 1*. Frankfurt: CreateSpace Independent Publishing Platform.
- Knapp Z (2018) *The Zooarchaeology of the Anglo-Saxon Christian Conversion: Lyminge, a case study*. PhD. University of Reading, Reading.
- Kruschke J (2014) *Doing Bayesian Data Analysis: A Tutorial with R, JAGS, and Stan*. 2nd ed. Boston: Academic Press.
- Kruschke JK (2013) Bayesian estimation supersedes the t test. *Journal of Experimental Psychology: General* 142(2): 573–603. DOI: 10.1037/a0029146.
- Kruschke JK and Liddell TM (2018) The Bayesian New Statistics: Hypothesis testing, estimation, meta-analysis, and power analysis from a Bayesian perspective. *Psychonomic Bulletin & Review* 25(1): 178–206. DOI: 10.3758/s13423-016-

- Kusaka S, Uno KT, Nakano T, et al. (2015) Carbon isotope ratios of human tooth enamel record the evidence of terrestrial resource consumption during the Jomon period, Japan. *American Journal of Physical Anthropology* 158(2): 300–311. DOI: 10.1002/ajpa.22775.
- Leggett S, Rose A, Praet E, and Le Roux P. Multi-Tissue and Multi-Isotope ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{18}\text{O}$ and $^{87/86}\text{Sr}$) Data for Early Medieval Human and Animal Palaeoecology. *Ecology* 102, no. 6 (2021): e03349. <https://doi.org/10.1002/ecy.3349>.
- Lightfoot E, Šlaus M, Šikanjić PR, et al. (2015) Metals and millets: Bronze and Iron Age diet in inland and coastal Croatia seen through stable isotope analysis. *Archaeological and Anthropological Sciences* 7(3): 375–386. DOI: 10.1007/s12520-014-0194-3.
- López-Costas O and Müldner G (2016) Fringes of the empire: Diet and cultural change at the Roman to post-Roman transition in NW Iberia. *American Journal of Physical Anthropology* 161(1): 141–154. DOI: 10.1002/ajpa.23016.
- Lucy S (2000) *The Anglo-Saxon Way of Death: Burial Rites in Early England*. Stroud: Sutton.
- Lucy S, Newman R, Dodwell N, et al. (2009) The Burial of A Princess? The Later Seventh-Century Cemetery At Westfield Farm, Ely. *The Antiquaries Journal* 89: 81. DOI: 10.1017/S0003581509990102.
- Mays S and Beavan N (2012) An investigation of diet in early Anglo-Saxon England using carbon and nitrogen stable isotope analysis of human bone collagen. *Journal of Archaeological Science* 39(4): 867–874. DOI: 10.1016/j.jas.2011.10.013.
- Müldner G (2016) Marine Fish Consumption in Medieval Britain: The Isotope Perspective from Human Skeletal Remains. In: Barrett JH and Orton DC (eds) *Cod and Herring: The Archaeology and History of Medieval Sea Fishing*. Oxford: Oxbow Books, pp. 239–249.
- Müldner G and Richards MP (2007) Stable isotope evidence for 1500 years of human diet at the City of York, UK. *American Journal of Physical Anthropology* 133: 682–697.
- Murtagh F and Legendre P (2014) Ward's Hierarchical Agglomerative Clustering Method: Which Algorithms Implement Ward's Criterion? *Journal of Classification* 31(3): 274–295. DOI: 10.1007/s00357-014-9161-z.
- O'Connell TC and Hull BD (2011) Diet: Recent Evidence from Analytical Chemical Techniques. In: *The Oxford Handbook of Anglo-Saxon Archaeology*. Oxford Handbooks. Oxford: Oxford University Press, pp. 667–687. DOI: 10.1093/oxfordhb/9780199212149.013.0034.
- O'Leary MH (1988) Carbon Isotopes in Photosynthesis. *BioScience* 38(5): 328–336. DOI: 10.2307/1310735.

- Orton D, Morris J and Pipe A (2017) Catch Per Unit Research Effort: Sampling Intensity, Chronological Uncertainty, and the Onset of Marine Fish Consumption in Historic London. *Open Quaternary* 3: 1. DOI: 10.5334/oq.29.
- R Development Core Team (2017) *R: A Language and Environment for Statistical Computing*. R. Available at: <http://www.r-project.org/>.
- Reynolds RV (2015) *Food for the Soul: The Dynamics of Fishing and Fish Consumption in Anglo-Saxon England: c. A.D. 410-1066*. PhD. University of Nottingham, Nottingham, UK.
- Richards MP, Fuller BT and Molleson TI (2006) Stable isotope palaeodietary study of humans and fauna from the multi-period (Iron Age, Viking and Late Medieval) site of Newark Bay, Orkney. *Journal of Archaeological Science* 33(1): 122–131. DOI: 10.1016/j.jas.2005.07.003.
- Rizzetto M, Crabtree PJ and Albarella U (2017) Livestock Changes at the Beginning and End of the Roman Period in Britain: Issues of Acculturation, Adaptation, and 'Improvement'. *European Journal of Archaeology* 20(3): 535–556. DOI: 10.1017/ea.2017.13.
- Robson HK, Andersen SH, Clarke L, Craig OE, Gron KJ, Jones AKG, Karsten P, et al. (2016) Carbon and Nitrogen Stable Isotope Values in Freshwater, Brackish and Marine Fish Bone Collagen from Mesolithic and Neolithic Sites in Central and Northern Europe. *Environmental Archaeology* 21, no. 2 (May 3, 2016): 105–18. <https://doi.org/10.1179/1749631415Y.0000000014>.
- RStudio Team (2019) *RStudio: Integrated Development Environment for R*. R. Boston, MA: RStudio, Inc. Available at: <http://www.rstudio.com/>.
- Sakai Y (2017) *Transition from the Late Roman Period to the Early Anglo-Saxon Period in the Upper Thames Valley Based on Stable Isotopes*. DPhil. University of Oxford, Oxford.
- Sayle KL, Hamilton WD, Cook GT, et al. (2016) Deciphering diet and monitoring movement: Multiple stable isotope analysis of the viking age settlement at Hofstaðir, Lake Mývatn, Iceland. *American Journal of Physical Anthropology* 160(1): 126–136. DOI: 10.1002/ajpa.22939.
- Serjeantson D and Woolgar CM (2006) Fish Consumption in Medieval England. In: *Food in Medieval England: Diet and Nutrition*. Medieval History and Archaeology. Oxford: Oxford University Press, pp. 102–130.
- Taylor GC, Hill JM, Jackson MC, Peel RA, and Weyl OLF (2017) Estimating $\Delta^{15}\text{N}$ Fractionation and Adjusting the Lipid Correction Equation Using Southern African Freshwater Fishes. *PLOS ONE* 12(5): e0178047. <https://doi.org/10.1371/journal.pone.0178047>.
- Tieszen LL and Fagre T (1993) Effect of Diet Quality and Composition on the Isotopic Composition of Respiratory CO_2 , Bone Collagen, Bioapatite, and Soft Tissues. In: Lambert JB and Grupe G (eds) *Prehistoric Human Bone: Archaeology at the Molecular Level*. Berlin/Heidelberg: Springer, pp. 121–155. DOI: 10.1007/978-

- Vallianatos H and Raine K (2008) Consuming Food and Constructing Identities among Arabic and South Asian Immigrant Women. *Food, Culture & Society* 11(3): 355–373. DOI: 10.2752/175174408X347900.
- van Wely M (2014) The good, the bad and the ugly: meta-analyses. *Human Reproduction* 29(8): 1622–1626. DOI: 10.1093/humrep/deu127.
- Vidal-Ronchas R, Rajić Šikanjić P, Premužić Z, et al. (2019) Diet, sex, and social status in the Late Avar period: stable isotope investigations at Nuštar cemetery, Croatia. *Archaeological and Anthropological Sciences* 11(5): 1727–1737. DOI: 10.1007/s12520-018-0628-4.
- Ward JH (1963) Hierarchical Grouping to Optimize an Objective Function. *Journal of the American Statistical Association* 58(301): 236–244. DOI: 10.2307/2282967.
- Weller DL and Turkon D (2015) Contextualizing the Immigrant Experience: The Role of Food and Foodways in Identity Maintenance and Formation for First- and Second-generation Latinos in Ithaca, New York. *Ecology of Food and Nutrition* 54(1). Routledge: 57–73. DOI: 10.1080/03670244.2014.922071.
- Whitelock D (1994) The laws of Wihtred, King of Kent (695). In: *English Historical Documents Volume I, c.500-1042*. English Historical Documents. London; New York: Routledge.
- Wilson TM (2006) Food, Drink and Identity in Europe: Consumption and the Construction of Local, National and Cosmopolitan Culture. In: *Food, Drink and Identity in Europe*. European Studies - An Interdisciplinary Series in European Culture, History and Politics, 22. Amsterdam: Editions Rodopi, pp. 11–30.
- Zhu M and Sealy J (2019) Multi-tissue stable carbon and nitrogen isotope models for dietary reconstruction: Evaluation using a southern African farming population. *American Journal of Physical Anthropology* 168(1): 145–153. DOI: 10.1002/ajpa.23731.
- Zuur AF, Ieno EN and Elphick CS (2010) A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution* 1(1): 3–14. DOI:10.1111/j.2041-210X.2009.00001.x.