A Hierarchical Meta-Analytical Approach to Western European Dietary Transitions in the First Millennium AD

SAM LEGGETT [ORCID]

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

During the first millennium AD, Europe saw much socio-environmental change, which is reflected in the archaeological and palaeoecological evidence. Using published and new isotope data from across western Europe, the author examines changing resource use from c. AD 350 to 1200. The geographical limits of millet and substantial marine consumption are identified and comparisons between childhood and adult diets made across regions. Cross-cultural interaction at a broad scale is emphasized and patterns within early medieval England form the subject of an in-depth case study. While doubt is cast onto the uptake of marine resource consumption in England following the Fish Event Horizon, changes in agricultural practices, the impact of Christianization, and the role of freshwater fish in diets are explored. The author's hierarchical meta-analytical approach enables identification of human–environment interactions, with significant implications for changing foodways in Europe during the first millennium AD.

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

INTRODUCTION

Between *c.* AD 350 and 1200, Europe witnessed considerable movement of people, ideas, and goods, reflecting cultural, religious, economic, and political change detectable to a greater and lesser degree in the archaeological record. In this article, I consider issues of change and dynamism by studying the isotopic signatures of people buried in late Antique and early medieval cemeteries, to capture socio-environmental interactions and transitions in the first millennium AD.

Everyone must eat and drink, and hence consumption is central to understanding the socioeconomics of the past— not just what people ate, but how they obtained it, commercialized it, traded it, stored it, cooked it, and thought about it. 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; Weller & Turkon, 2015).

Biomolecular archaeology gives us a unique toolkit for studying foodways, mobility, past individuals and their bodies, and the contexts in which they lived. This toolkit can be used at both individual and population scales, which makes it very versatile. Within biomolecular archaeology, isotopic analyses use the chemical memories of past events stored in the tissues of the dead to inform us about their lives, helping us to better understand resource

exploitation, agriculture, the economy, foodways, and identity.

This article presents an integrated large-scale meta-analysis of collagen isotopic data for the first millennium AD in England and western Europe. It is believed to be the first of its kind at this scale: previous studies have been smaller and more focused assessments of isotopic data (e.g. O'Connell & Hull, 2011; Mays & Beavan, 2012; Hannah et al., 2018). The aim is to better identify and assess the impact of major transitional events such as changes in agricultural practice and the 'Fish Event Horizon'. Further, the goal is to compare, contrast, and quantify regional dietary variation for the period. England is at the core of this study for two reasons: it has the most isotopic data available for any region in the period between *c.* AD 350 and 1200 and it has arguably been more heavily affected by the events noted above, making it an ideal case study to track dietary transitions.

BASIC PRINCIPLES OF STABLE ISOTOPE ANALYSIS

Stable isotope analysis in archaeology is a well-established technique. It is based 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).

Carbon stable isotope ratios can discern between diets based on C_3 plants and C_4 plants and are useful in differentiating between marine and terrestrial food resources (O'Leary, 1988). Nitrogen stable isotope ratios indicate the position of an organism in the food chain, and increase ~3–5‰ per level of the food chain (Bocherens & Drucker, 2003; Lucy et al., 2009); $\delta^{15}N$ can also be altered by factors

such as breastfeeding, pregnancy, and periods of nutritional stress (Fuller et al., 2005; Beaumont et al., 2015).

The carbon in enamel is derived from blood carbonate, which in turn comes from metabolism and is thought to represent whole diet (protein, fats, and carbohydrates) (Ambrose & Norr, 1993; Tieszen & Fagre, 1993; Hedges, 2003; Zhu & Sealy, 2019). Calculating the differences between enamel, bone, and dentine can therefore narrow down trophic level and dietary changes through life.

FIRST MILLENNIUM AD DIETARY TRANSITIONS

Here, I focus on how isotopic signatures record human–environment interactions, how major socio-environmental change may disrupt these patterns, and whether these transitions were widespread in western Europe. Indeed, events such as the agricultural 'revolution' of the eighth to thirteenth centuries AD, Christianization (in the seventh–eighth centuries in England), and the 'Fish Event Horizon' of *c.* AD 1000 represent significant socio-economic shifts that had an impact on foodways across western Europe, including England.

The re-introduction of Christianity to eastern England had political and economic implications; it may have affected diet, mainly through religious dietary laws such as those of Wihtred of Kent (*c.* AD 695) that imposed fines on those eating meat during fasting (Whitelock, 1996). This allows us to investigate orthopraxy through the archaeological record (Barrett, 2003; Knapp, 2018: 290-300; 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 cultivated, alongside technological innovations like the mouldboard plough. This

supported growing urban communities and facilitated changes in power structures across much of Europe, especially England (Duby, 1997; Banham & Faith, 2014; Dyer et al., 2018; Hamerow et al., 2020).

The 'Fish Event Horizon' (FEH hereafter) constitutes another key dietary shift evident in the zooarchaeological record of Europe around AD 1000 (Barrett et al., 2004a, 2004b). It refers to 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 & Woolgar, 2006; Reynolds, 2015: 230-96; Barrett, 2016; Orton et al., 2017). Such a major shift towards marine consumption should be evident in the human isotopic data, but this has so far not been studied with a large human isotopic dataset (Reynolds, 2015: 212-22, 295; Barrett, 2016; Müldner, 2016).

These large-scale transitions and human adaptations demand a broad-scale approach, using meta-analytical methods for compiling and analysing the data. Computational meta-analyses are highly complex and an emerging style of research in archaeology; they are 'neither quick nor easy' (Berman & Parker, 2002) due to the challenges of data standardization, cross-study comparisons, and the statistical difficulties they pose (Greco et al., 2013; van Wely, 2014). The following section briefly summarizes the approach taken.

MATERIALS AND METHODS

The dataset comprises 5334 human isotopic entries from twenty-six modern countries and 200 sites (Figure 1). It is a subset of the entire dataset described in detail in Leggett et al. (2021), which includes further bioapatite data not analysed here. While 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, using legacy data and newly generated isotopic data from England.

The regional designations in Figure 1 were created to limit the use of current political boundaries and the problematic use of ethnic identifiers for past geo-political zones, while also incorporating some of the environmental and geological variation across Europe. The zonation resulted from plotting the sites to look for spatial clustering and adjusting these with $\delta^{18}O$ and $^{87/86}Sr$ isoscapes (Evans et al., 2010, 2012, 2018; Bataille et al., 2020), as well as cultural factors such as grave good styles and linguistic aspects (for details see Leggett et al., 2021).

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 at https://doi.org/10.17605/OSF.IO/6B8MZ. Full data compilation and standardization details are available in Leggett et al. (2021) and further details on statistical analyses are available in the online Supplementary Material.

Archaeological data are often subject to strong 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 (e.g. European region, region within England, environment type, site), varying numbers of sexes, genders, age groups, and funerary treatments for individuals, and date ranges across 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,
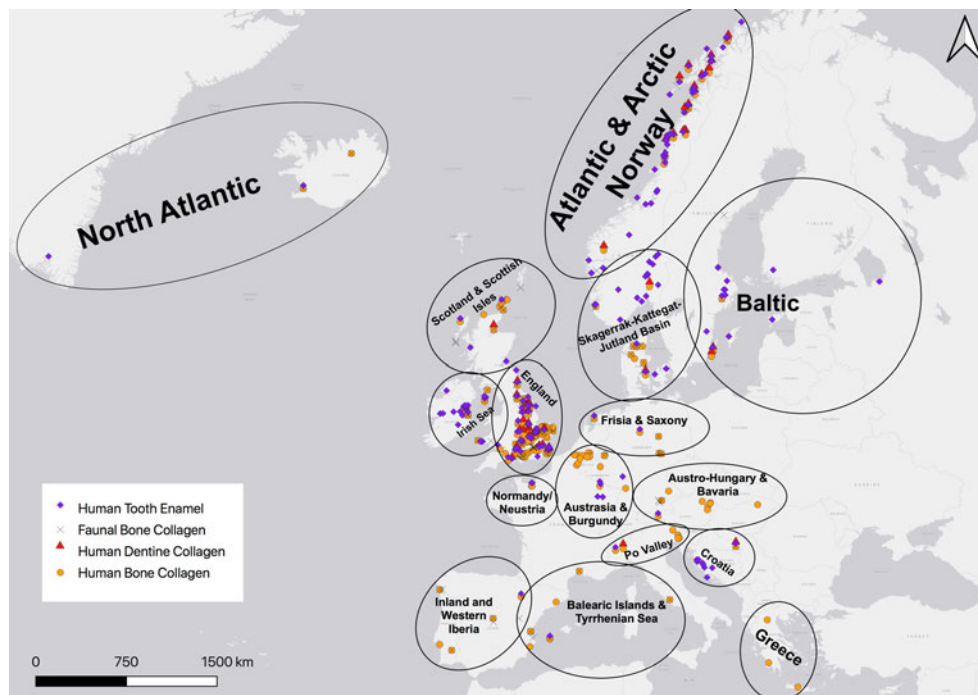
Figure 1. *Map of sites (after Leggett et al., 2021) analysed in this article, the tissues present, and their geo-cultural regional designations.*

which require user determination of the number of clusters in the dataset (e.g. k-means). I used Ward's hierarchical agglomerative clustering method and the Ward2 algorithm (Ward, 1963; Murtagh & Legendre, 2014; Kassambara, 2017). This was cross-validated using thirty-two indices (see Supplementary Material).

Hierarchical clustering was visualized as a dendrogram showing the data structure and proximity of individuals to one another within this structure. The clusters were then used to colour scatterplots for each tissue to better highlight the isotopic niches they represent. The clusters were also visualized 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 in different geo-cultural regions.

BEST (Bayesian Estimation Supersedes the t-test) tests were used to compare between groups, run with R package BEST (for more details see Kruschke, 2013 and Supplementary Material).

Burials were assigned to chronological periods on the basis of radiocarbon dates or numismatic evidence where available and, when unavailable, grave goods (Hines & Bayliss, 2013; Brownlee, 2019; Leggett et al., 2021). Given the small sample sizes for most regions, chronological analyses were confined to England.

Bone and dentine data are presented separately below as few individuals have isotopic data from both tissues, and so integrated clustering would be extremely limited.

FOODWAYS AND DIET IN EUROPE DURING THE FIRST MILLENNIUM AD

Isotopic characterization and comparison across and within regions of western

Europe were conducted to identify broad-scale patterns in foodways and diets, recognize dietary differences and trends over the first millennium AD, investigate the impact of events such as the FEH, and determine their geographical origins and spread.

As outlined above, hierarchical cluster analyses were undertaken for both bone (n = 4139) and dentine (n = 931) collagen $\delta^{13}C$ and $\delta^{15}N$ values.

Bone data

The data structure and isotopic ranges of the clusters can be seen 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 $\delta^{15}N_{coll}$ values. Bone cluster 2.2 is distinguished predominantly by its less negative $\delta^{13}C_{coll}$ values and lower $\delta^{15}N_{coll}$ values compared to cluster 2.1.

A north-south trend 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, in particular marine food consumption, may have originated.

Cluster 1 is particularly dominant in 'Germanic' areas of continental Europe, Ireland, and Britain (especially England, with 1899 out of 2917 samples in that cluster). The North Atlantic islands and Greece have over fifty per cent 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 possible marine consumers). Figure 4 highlights that Scandinavia and the Baltic dominate this cluster, which supports a cultural genesis of the FEH in Scandinavia

(Barrett et al., 2004a, 2016; Barrett & Richards, 2004). This cluster is the most dominant in Atlantic and Arctic Norway, the Baltic, Scotland, and the Scottish Islands, but not significantly present elsewhere. An absence of evidence for 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 are dated from the seventh century onwards. This may therefore be better interpreted as a more generalized nitrogen enrichment watershed, and not solely a marine-based transition. Cluster 2.1 with its higher $\delta^{15}N_{coll}$ bone values does not represent an ubiquitous marine-based FEH across Europe; instead, it may show an increase in meat consumption more broadly, and possibly a FEH with a greater freshwater component, as indicated by the enamel $\delta^{13}C_{carb}$ values of some individuals.

Cluster 2.2 is dominant in, and dominated by, the Mediterranean and parts of central and eastern Europe. First, this shows the regionally distinctive consumption of millet and other C_4 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). Second, it indicates interactions across the Mediterranean with North Africa and the introduction of C_4 plants through Iberia and the Balearic Islands, probably via late Roman and Islamic influences (López-Costas & Müldner, 2016; Guede et al., 2017; Alaica et al., 2019; Alexander et al., 2019; Dury et al., 2019; García-Collado et al., 2019; Jordana et al., 2019). Third, it represents individuals who are exploiting lower trophic level marine resources or consuming smaller proportions of marine resources compared with those in cluster 2.1 (Bourbou & Richards, 2007; Bourbou et al., 2011; Dury et al., 2019).
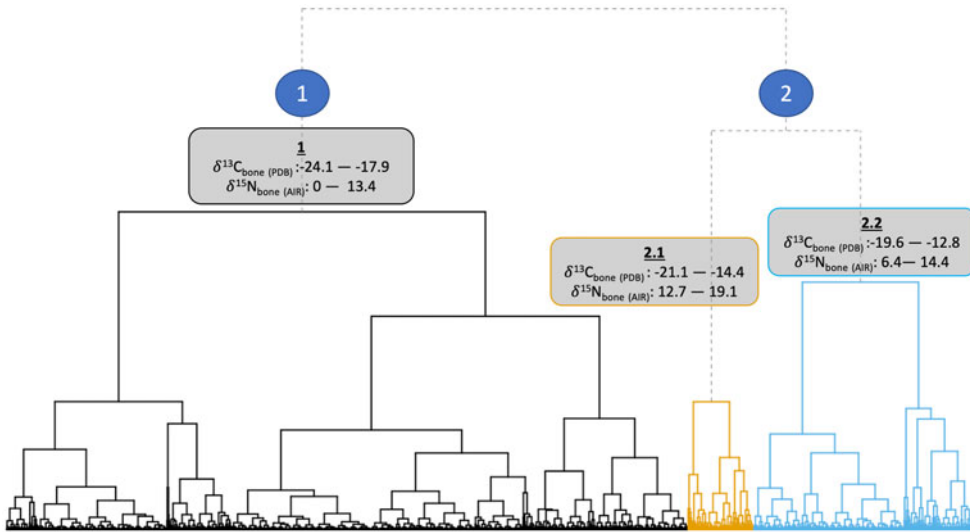
Figure 2. *Ward's method (1963) hierarchical clustering dendrogram of first-millennium AD western European human bone $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ stable isotope values (n = 4139).*

The geographical boundaries for fifty per cent or fewer inclusion in clusters 2.1 and 2.2 are in Scotland and Central Europe, respectively. These resource or foodways boundaries match historical and archaeological evidence, which shows these regions to be key areas of contact with the Viking and Steppe groups who are credited with introducing the FEH and millet cultivation respectively (Barrett et al., 2004a;

Figure 3. *Scatterplot of $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ of first-millennium AD western European human bone coloured by cluster number determined by analyses illustrated in Figure 2.*
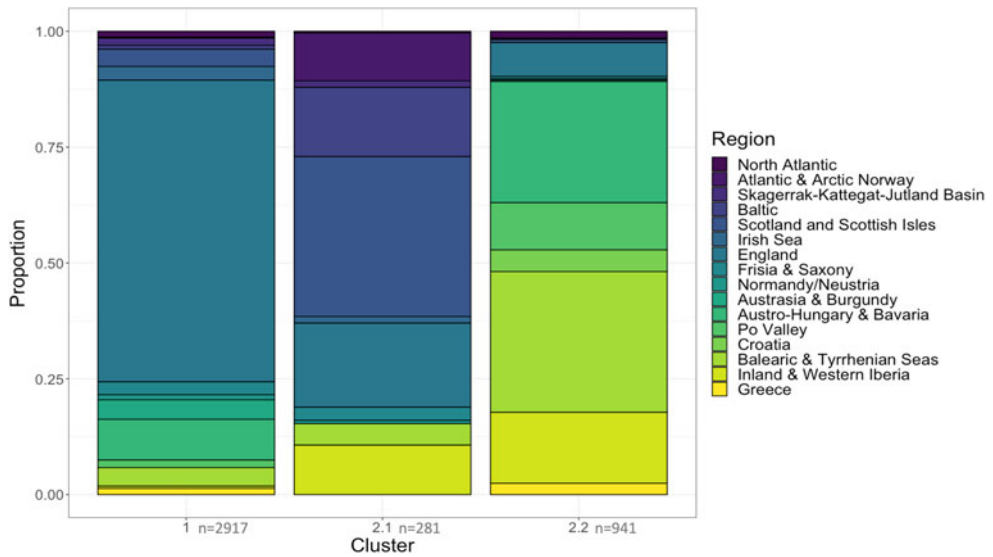
Figure 4. *Proportion of individuals in each bone $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ cluster coloured by region.*

Barrett & Richards, 2004; Richards et al., 2006; Hakenbeck et al., 2017; Amorim et al., 2018; Vidal-Ronchas et al., 2019; Filipović et al., 2020).

Some exceptions are notable. The lack of marine consumption in the North Atlantic appears to be due to more terrestrial and freshwater resources being consumed, as determined by sulphur stable isotope analysis (Sayle et al., 2016). The less than forty per cent proportion of individuals in Greece in cluster 2.2 suggests
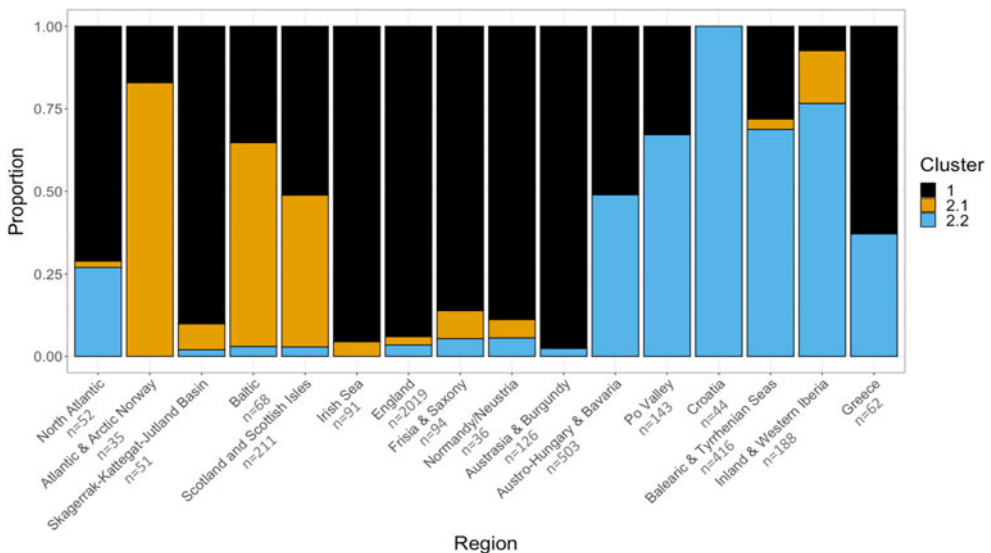

Figure 5. *Proportion of individuals in each region coloured by $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ bone cluster, using the same colour scheme as Figures 2 and 3.*

that Byzantine Greek diets were hardly influenced by central Asian millet consumption; instead, they are more based on terrestrial C_3 plants and low-trophic marine resources (Bourbou & 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 in Croatia that had signatures more consistent with C_3 diets in cluster 2.2, perhaps reflecting close similarities in this and neighbouring populations or perhaps a mixing of C_3 and C_4 resource consumption and the limited sample size.

Hierarchical clustering of bone isotopic values in England confirms the dominance of foods from C_3 ecosystems. England's cluster profile in Figure 5 most resembles the Skagerrak-Kattegat-Jutland Basin, Frisia and Saxony, and Normandy/ Neustria. These regions are among England's nearest neighbours, with climatic and environmental similarities. These three neighbouring regions are areas with historically and isotopically attested migration into England during our period and have themselves seen migration from Norway, Sweden, and the Baltic. Their environmental similarities and migrant histories may thus explain these dietary profiles. Furthermore, among the individuals assigned to clusters 2.1 and 2.2 in the database, the Fennoscandian and Baltic routes attested by these minority diets are even clearer.

Cluster 2.1 individuals in England mostly date from 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 (such as monasteries or churchyards, e.g. Caister-by-Yarmouth and Raunds Furnells). These individuals illustrate a dual aspect of the FEH in England; that is, introduced Scandinavian marine consumption and Christian foodways with fish and fowl taking the place of other meats.

The interpretation of individuals in cluster 2.2 in England is slightly more complex. They are predominantly from Late Roman cemeteries of the third to fifth centuries AD, and hence represent markedly different foodways compared to early medieval sites. Twenty-two of the sixty-nine individuals assigned to cluster 2.2 date to 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). Their chronology and context place these individuals into the category of marine consumers who occupy a lower trophic position compared to those in cluster 2.1, who may also have consumed a high proportion of C_3 resources, which reflects both Scandinavian and Christian foodways.

Dentine data

The same process was applied to human dentine values to compare the signatures from childhood and earlier life diets with those obtained from bone. The dendrogram structure and isotopic ranges of clusters for dentine are very similar to those for bone, with two major branches (Figure 6). This is then visualized as a scatterplot in Figure 7.

Dentine cluster 1 is the largest, with 552 samples. It corresponds to bone cluster 1 and represents C_3-based diets across several trophic levels. Dentine cluster 2.1 roughly equates with bone cluster 2.2, and likewise has the smallest sample size, with thirty-four samples. Dentine cluster 2.1 is assumed here to represent C_4/marine based diets with a $\delta^{15}N_{coll}$ value range similar to that of cluster 1. Cluster 2.2 differs from the other two groups for having higher $\delta^{15}N_{coll}$ values and equates with bone
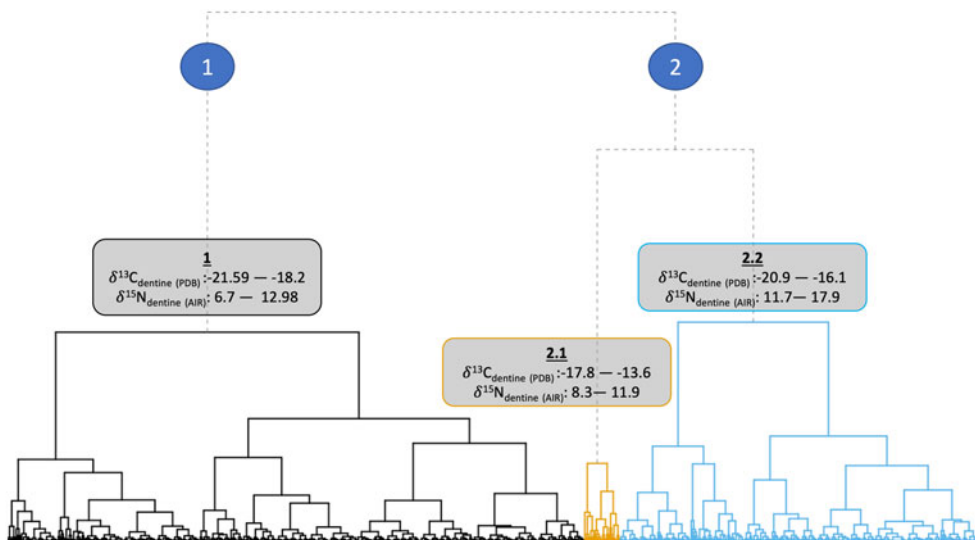
Figure 6. *Ward's method (1963) hierarchical clustering dendrogram of first-millennium AD western European human dentine $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ stable isotope values (n = 931).*

cluster 2.1. As with bone, individuals in this higher trophic level group appear to be mostly C_3 terrestrial or freshwater protein consumers, although a small number do have $\delta^{13}C_{coll}$ values that overlap with cluster 2.1. These individuals may have therefore been consuming a higher proportion of marine resources or
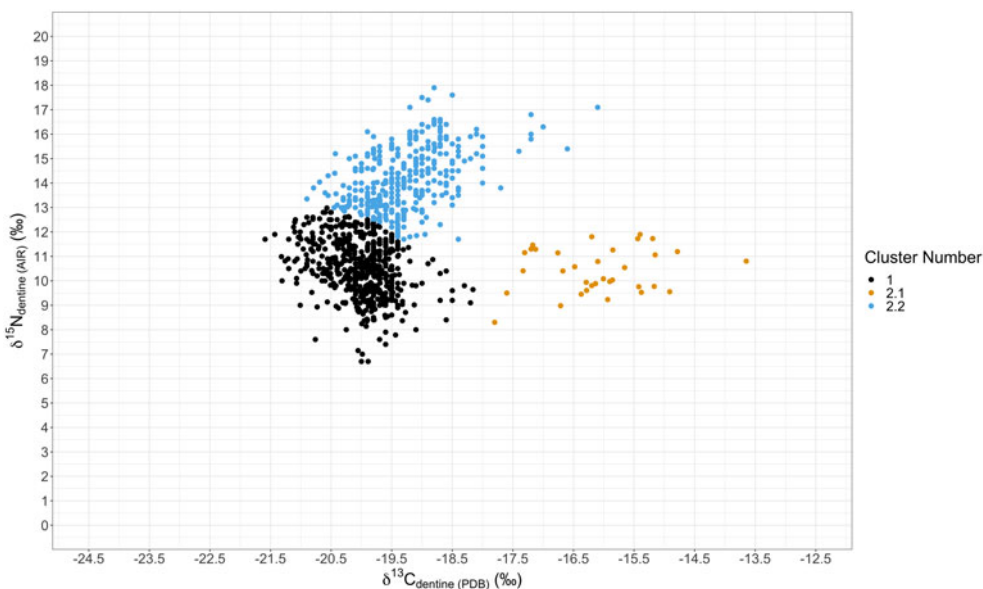

Figure 7. *Scatterplot of $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ from first-millennium AD western European human dentine coloured by cluster number determined by analyses illustrated in Figure 6.*
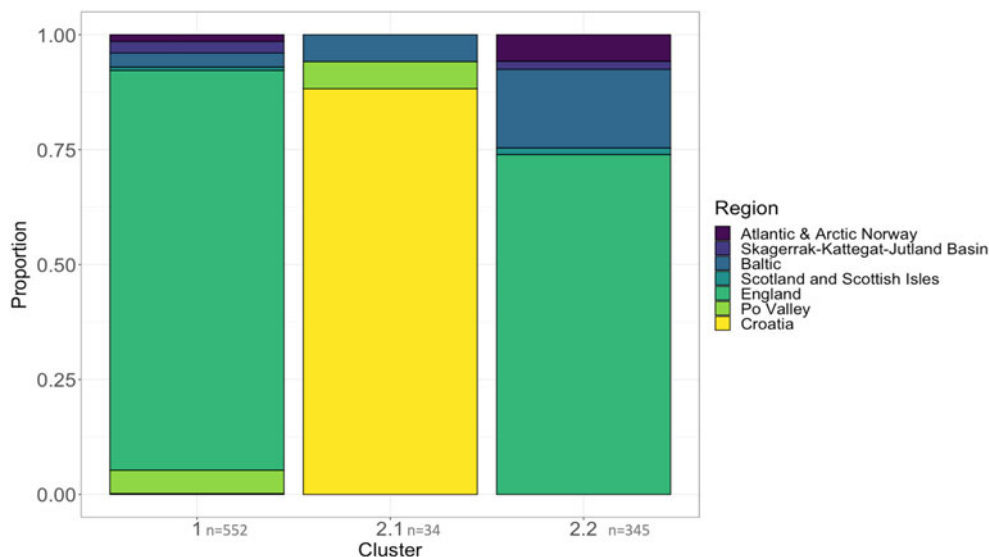
Figure 8. *Proportion of individuals in each dentine $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ cluster coloured by region.*

animals fed on C_4 plants than those in cluster 2.1, or had a mixed terrestrial/marine diet.

The regional make-up of the clusters and proportions of clusters are shown in Figures 8 and 9. Due to the reduced number of regions represented in the dentine data, regional diversity in clusters is not as high as that of bone. Nonetheless, the dentine data support the findings from bone, with a pattern running northwest-southeast across Europe in both datasets.

Dentine cluster 1, representing the C_3 terrestrial/freshwater consuming cluster, is found in every region, although dominated by England. The highest proportions are found there, as well as in the Po Valley and the Skagerrak-Kattegat-Jutland Basin.

Dentine cluster 2.1 comprises almost entirely individuals buried in Croatia, with a handful of instances from the Po Valley and the Baltic. There is a clear difference between the dentine and bone from the Po Valley, which suggests a change from a more C_3-based diet in childhood to consumption of more C_4 resources later in life. The Baltic is the only region with all

three clusters present, which mirrors its isotopic variability for bone. However, one individual assigned to dentine cluster 2.1 in the Baltic is an outlier for the region and site, Triberga on the island of Öland (Howcroft et al., 2012), and could represent a migrant from one of the C_4 consuming regions discussed here, or further afield.

Dentine cluster 2.2 is dominated by individuals from England (255 out of 345 samples), the rest being present in Scotland and the Fennoscandian regions. The proportions of this cluster in each region mirrors the trend for bone, with higher proportions of people with ^{15}N enrichment found in Atlantic and Artic Norway, and the Baltic. England and the Skagerrak-Kattegat-Jutland Basin again closely resemble each other. Individuals in England assigned to dentine cluster 2.2 were predominantly buried in later churchyards (e.g. Black Gate Newcastle or Raunds Furnells) or from sites with known Viking links (Ridgeway Hill). There are six earlier individuals dating to the sixth–eighth centuries AD. These
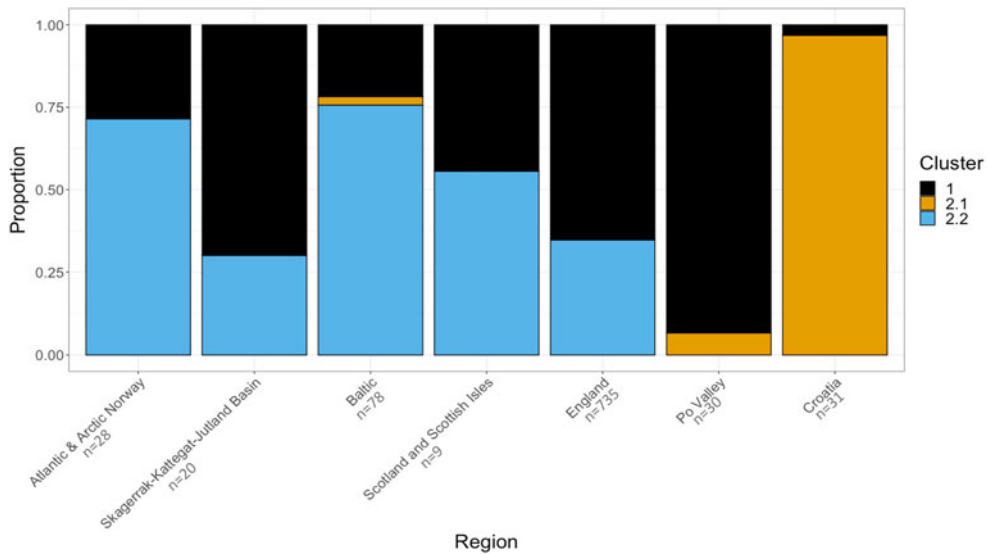
Figure 9. *Proportion of individuals in each region coloured by $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ dentine cluster, using the same colour scheme as Figures 6 and 7.*

burials are outliers for their cemeteries in this cluster assignment; perhaps they were migrants as they are all older adults, and bar one child from Southam (with an earlier forming tooth), post-weaning teeth were sampled.

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 presented above suggest this had a minimal impact on the overall results. For most regions, childhood and adult diets appear very similar.

DIACHRONIC CHANGE WITHIN ENGLAND

To test the cause(s) for the isotopic variability presented above, the data for England were assessed chronologically to identify any changes in diet and align them with the first-millennium transitions outlined above.

Figure 10c shows much overlap between diets in England across all three chronological phases, but with noticeable changes in $\delta^{15}N$ values. It is tempting to equate the change in the period *c.* AD 790–1066 and later as evidence for the FEH, but, if we examine changes in $\delta^{13}C_{coll}$ (Figure 10a) and $\delta^{15}N_{coll}$ (Figure 10b) values separately, this interpretation is no longer tenable.

A dietary shift from the Roman period to the Early Middle Ages is evident in both $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ values, with a drop in $\delta^{13}C_{coll}$ values at the end of the Roman period, possibly reflecting a range 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' illustrated in Figure 10c and d, however, supports theories that a high level of dietary continuity (in terms of isotopic signatures) existed between these periods (Banham & Faith, 2014; Sakai, 2017: 10, 151-53, 310-15). This shift is backed by a BEST test, but equates to a difference in posterior predictive means of 0.73‰, which is not large.
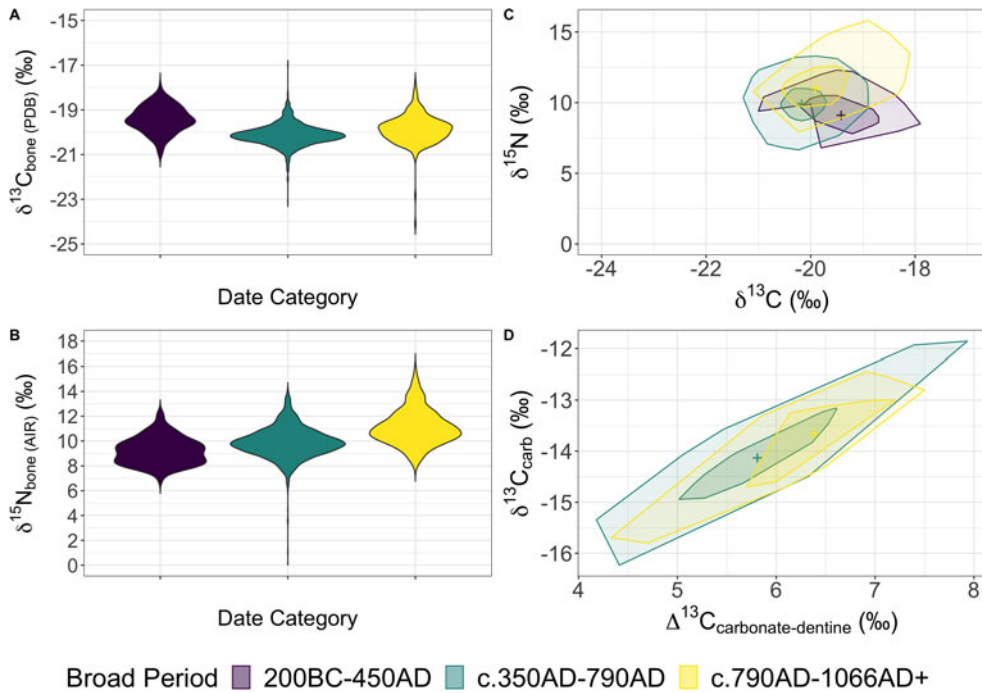
Figure 10. *Bone collagen $\delta^{13}C$ and $\delta^{15}N$ values from England through time. A) $\delta^{13}C_{coll}$ values; B) $\delta^{15}N_{coll}$ values, C) bag plots of $\delta^{13}C$ and $\delta^{15}N$ values; D) bag plots of $\Delta^{13}C_{enamel-dentine}$ and $\delta^{13}C_{carb}$. For plots A, B, and C, n = 187 for Roman (purple), n = 1603 for c. fourth–eighth century (teal), and n = 229 for late eighth–thirteenth century (yellow). For plot D, n = 176 and n = 34 for teal and yellow respectively.*

The strong peak and overall shift in distribution to more negative $\delta^{13}C_{coll}$ values nevertheless adds weight to the argument that freshwater resource consumption increased, and agricultural changes occurred during the early Middle Ages.

The differences in distribution shape and range show more variety in bone $\delta^{13}C_{coll}$ values for the later period, with a C_3 diet of both terrestrial and freshwater resources and no substantial or widespread marine consumption in adulthood. The bone $\delta^{15}N_{coll}$ data in Figure 10b shows increasing means, maximum values, and more positively shifted distributions over time. BEST tests confirm that these shifts are real, albeit 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 Christianization and changing worldviews on death and the afterlife have been suggested (Reynolds, 2015: 189-91, 278-96; Knapp, 2018: 290-300; Brownlee, 2021; Leggett, 2021). The clear spike in bone $\delta^{15}N_{coll}$ values from the eighth century onwards is not accompanied by the corresponding increase in $\delta^{13}C_{coll}$ to support a marine FEH in England close to AD 1000, as previously argued (Barrett et al., 2004a, 2004b; Barrett, 2016; Müldner, 2016; Orton et al., 2017). Nitrogen enrichment with stable carbon isotopic values in post-Roman England instead supports the notion that other dietary changes took place, such as an increase in the intake of freshwater/

terrestrial protein, or agricultural innovations that would increase $\delta^{15}N$ values in cereal crops, as seen in the archaeobotanical isotopic evidence from Stafford (Hamerow et al., 2020). Crop isotope data from Stafford (*c.* AD 800–1200) 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 $\delta^{13}C$ values remaining mostly stable with some decrease in values. Alongside the weed ecology and pollen data, the investigators believe that this change is due to crop extensification and the adoption of the mouldboard plough to cultivate more nitrogen-rich soils, and not to manuring; moreover, such isotope values were likely to be passed onto consumers (Hamerow et al., 2020).

To investigate these possibilities, $\Delta^{13}C_{enamel\text{-}dentine}$ values (the difference between $\delta^{13}C$ values of enamel and dentine) 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. greater in herbivores, smaller in carnivores; Clementz et al., 2009); $\Delta^{13}C_{bioapatite\text{-}collagen}$ 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 & Koch, 2001; Clementz et al., 2007, 2009; Kusaka et al., 2015). For the small proportion of individuals in the period *c.* AD 790–1066 and later with higher trophic levels ($\Delta^{13}C_{enamel\text{-}dentine}$ values of ~4‰), Figure 10d shows that their $\delta^{13}C_{carb}$ values could indicate their trophic position is due to ^{13}C depletion in freshwater organism lipids (Robson et al., 2016; Taylor et al., 2017; Guiry, 2019). This would affect the $\delta^{13}C_{carb}$ values over $\delta^{13}C_{coll}$ in consumers due to differential dietary routing. This is also observed in the

earlier period (*c.* AD 350–790), with a strong trend in both broad periods. A high degree of overlap between these two periods, with a high degree of variability in diets in the earlier period, is not as evident in Figure 10b and c, where chronological change from *c.* AD 790 is more apparent.

While I agree with Müldner (2016) that there is no evidence for any large-scale marine consumption in the post-Roman/pre-Viking periods, I would go further: aside from a few outlying individuals with some tenuous marine dietary signatures, there is also no evidence from multi-tissue analyses for the FEH in England up to the eleventh century. For bone, 119 out of 2023 $\delta^{13}C$ and $\delta^{15}N$ signatures in England are classified by UML as belonging to bone cluster 2.1 or 2.2 (marine/C_4 diets); forty-nine of these are late Roman and a further twenty-three are juveniles from Raunds Furnells, and probably represent osteological paradox (physiological stress leading to 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 & Stojanowski, 2015). Many of the remaining forty-seven examples in clusters 2.1 and 2.2 have strong Scandinavian ties and are assumed to be migrants (Ketton Quarry, Repton, St John's College, Oxford) with signatures seemingly largely extraneous to England. For the fifty individuals with bone $\delta^{13}C$ and $\delta^{15}N$ values confidently dated to AD 1000–1400, strong marine dietary signatures are not the norm (only five individuals from York dating to *c.* AD 1050–1200 are categorized as having cluster 2.1 bone signatures; see Leggett et al., 2021), but more post-AD 1000 samples are needed. The key point is that multi-isotope and multi-tissue evidence in various combinations, and the use of these to create tissue offsets and enrichment factors, can contribute to a

better assessment of trophic levels and show freshwater resource consumption; and the application of UML on these large datasets can 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; but the lack of a marked increase in bone $\delta^{13}C$ through time, and tissue enrichment factors alongside enamel carbonate, indicates that this shift in $\delta^{15}N_{coll}$ values post-AD 790 is not in fact a marine FEH. There is clear isotopic evidence for freshwater resource consumption that matches fish bone assemblages from London, where catch per unit increases in the seventh century AD (Orton et al., 2017). Zooarchaeological evidence for both freshwater and marine species spikes considerably around AD 1000 in London and other parts of Britain, which is not fully supported by the human isotopic evidence here (Barrett et al., 2004a; Barrett & Richards, 2004; Serjeantson & Woolgar, 2006; Reynolds, 2015: 80-115, 212-22, 237-38; Orton et al., 2017).

How can we reconcile this? There is evidence for freshwater consumption, more so in *c.* AD 350–90, 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 $\delta^{15}N_{coll}$ values (from either tissue) above ~8‰, with 'herbivorous' $\Delta^{13}C_{enamel-dentine}$ values in some individuals? One possible explanation comes from Stafford, where extensification practices causing crop ^{15}N enrichment and minor ^{13}C depletion, passed onto human consumers, could cause the patterns seen here. To explore this hypothesis, further analysis of human, wild herbivore, and plant isotopes from the same site would be needed. If the increased demand for marine fish seen in the zooarchaeological evidence comprised less than twenty per cent of whole diets, the signature would be isotopically and metabolically swamped by terrestrial/freshwater signatures and hence invisible in the collagen signatures presented here. This may point to a more plant-based explanation for changes in diet over time.

CONCLUSIONS

A meta-analytical approach to categorizing human isotopic niches highlights the need for multi-tissue studies when considering diet. The outcomes from using UML methods also underline the need to reconsider how statistics are used in archaeological stable isotope studies. While some of the trends identified here may seem intuitive, UML allows isotopic data users to explore clustering *a priori*, removing user determination. This makes it possible to avoid biasing cluster construction and ensures more robust archaeological interpretations of cluster patterning.

The clear north-south trend in bone and dentine dietary signals across Europe indicates that more marine-based diets in Scandinavia were introduced further south through settlement, and that C_4 crops and migrants with substantial C_4 diets gradually came from the east. Most people in western Europe, however, had a C_3-based diet in both childhood and adulthood. Nitrogen enrichment over time in England cannot be linked directly to the FEH. Instead, the diachronic change observed supports the notion that foodways changed under the influence of Christian orthopraxy and the agricultural revolution of the eighth to thirteenth centuries, reflecting changes in both the economy and in worldviews. The first millennium AD and the early centuries of the second millennium was a time when complex societies were in sustained cross-cultural contact, forming part of large

sub-continental networks that influenced change in material culture, foodways, and thought.

ACKNOWLEDGEMENTS

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/eaa.2022.23.

REFERENCES

Alaica, A.K., Schalburg-Clayton, J., Dalton A, Kranioti, E., Graziani Echávarri, G. & Pickard, C. 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: 3783–96. https://doi.org/10.1007/s12520-018-0656-0

Alexander, M.M., Gutiérrez, A., Millard, A.R., Richards, M.P. & Gerrard, C.M. 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*, 11: 3875-93. https://doi.org/10.1007/s12520-019-00810-x

Ambrose, S.H. & 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: J.B. Lambert & G. Grupe, eds. *Prehistoric Human Bone*. Berlin & Heidelberg: Springer, pp. 1–37. https://doi.org/10.1007/978-3-662-02894-0_1

Amorim, C.E.G., Vai, S., Posth, C., Modi, A., Koncz, I., Hakenbeck, S., et al. 2018. Understanding 6th-Century Barbarian Social Organization and Migration Through Paleogenomics. *Nature Communications*, 9: 1–11. https://doi.org/10.1038/s41467-018-06024-4

Banham, D. & Faith, R. 2014. Continuities and Changes in Arable Husbandry. In: D. Banham & R. Faith, eds. *Anglo-Saxon Farms and Farming*. Oxford: Oxford University Press, pp. 269–92. https://doi.org/10.1093/acprof:oso/9780199207947.001.0001

Barrett, J.H. 2003. Christian and Pagan Practice during the Conversion of Viking Age Orkney and Shetland. In: M.O.H. Carver, ed. *The Cross Goes North: Processes of Conversion in Northern Europe, AD 300-1300*. Woodbridge & Rochester (NY): Boydell & Brewer, pp. 207–27.

Barrett, J.H. 2016. Medieval Sea Fishing, AD 500–1550: Chronology, Causes and Consequences. In: J.H. Barrett & D.C. Orton, eds. *Cod and Herring: The Archaeology and History of Medieval Sea Fishing*. Oxford: Oxbow Books, pp. 250–72.

Barrett, J.H. & Richards, M.P. 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: 249–71. https://doi.org/10.1177/1461957104056502

Barrett, J.H., Locker, A.M. & Roberts, C.M. 2004a. 'Dark Age Economics' Revisited: The English Fish Bone Evidence AD 600–1600. *Antiquity*, 78: 618–36. https://doi.org/10.1017/S0003598X00113262

Barrett, J.H., Locker, A.M. & Roberts, C.M. 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: 2417–21. https://doi.org/10.1098/rspb.2004.2885

Barrett, J.H., Orton, D., Johnstone, C., Harland, J., Van Neer, W., Ervynck, A., 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: 1516–24. https://doi.org/10.1016/j.jas.2011.02.017

Bataille, C.P., Crowley, B.E., Wooller, M.J. & Bowen, G.J. 2020. Advances in Global Bioavailable Strontium Isoscapes. *Palaeogeography, Palaeoclimatology, Palaeoecology*: 109849. https://doi.org/10.1016/j.palaeo.2020.109849

Bayliss, A., Shepherd Popescu, E., Cook, G., Bronk Ramsey, C. & Beavan-Athfield, N. 2009. Radiocarbon Dating. In: E. Shepherd Popescu, ed. *Norwich Castle: Excavations and Historical Survey 1987–98. Part I Anglo-Saxon to c. 1345* (East Anglian Archaeology 132). Gressenhall: Norfolk Archaeological Unit Archaeology & Norfolk Historic Environment, pp. 237–53.

Beaumont, J., Montgomery, J., Buckberry, J. & Jay, M. 2015. Infant Mortality and Isotopic Complexity: New Approaches to Stress, Maternal Health, and Weaning. *American Journal of Physical Anthropology*, 157: 441–57. https://doi.org/10.1002/ajpa.22736

Berman, N.G. & Parker, R.A. 2002. Meta-Analysis: Neither Quick nor Easy. *BMC Medical Research Methodology*, 2: 10. https://doi.org/10.1186/1471-2288-2-10

Bocherens, H. & 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: 46–53. https://doi.org/10.1002/oa.662

Bourbou, C. & Richards, M.P. 2007. The Middle Byzantine Menu: Palaeodietary Information from Isotopic Analysis of Humans and Fauna from Kastella, Crete. *International Journal of Osteoarchaeology*, 17: 63–72. https://doi.org/10.1002/oa.855

Bourbou, C., Fuller, B.T., Garvie-Lok, S.J. & Richards, M.P. 2011. Reconstructing the Diets of Greek Byzantine Populations (6th–15th Centuries AD) Using Carbon and Nitrogen Stable Isotope Ratios. *American Journal of Physical Anthropology*, 146: 569–81. https://doi.org/10.1002/ajpa.21601

Brownlee, E.C. 2019. Burial Practices in Transition: A Study of the Social, Cultural and Religious Cohesion of Early Medieval Europe (unpublished PhD dissertation, University of Cambridge).

Brownlee, E.C. 2021. Connectivity and Funerary Change in Early Medieval Europe. *Antiquity*, 95: 142–59. https://doi.org/10.15184/aqy.2020.153

Clementz, M.T. & Koch, P.L. 2001. Differentiating Aquatic Mammal Habitat and Foraging Ecology with Stable Isotopes in Tooth Enamel. *Oecologia*, 129: 461–72. https://doi.org/10.1007/s004420100745

Clementz, M.T., Fox-Dobbs, K., Wheatley, P.V., Koch, P.L. & Doak, D.F. 2009. Revisiting Old Bones: Coupled Carbon Isotope Analysis of Bioapatite and Collagen as an Ecological and Palaeoecological Tool. *Geological Journal*, 44: 605–20. https://doi.org/10.1002/gj.1173

Clementz, M.T., Koch, P.L. & Beck C.A. 2007. Diet Induced Differences in Carbon Isotope Fractionation between Sirenians and Terrestrial Ungulates. *Marine Biology*, 151: 1773–84. https://doi.org/10.1007/s00227-007-0616-1

Cook, I. 2008. Geographies of Food: Mixing. *Progress in Human Geography*, 32: 821–33. https://doi.org/10.1177/0309132508090979

DeWitte, S.N. & Stojanowski, C.M. 2015. The Osteological Paradox 20 Years Later: Past Perspectives, Future Directions. *Journal of Archaeological Research*, 23: 397–450. https://doi.org/10.1007/s10814-015-9084-1

Duby, G. 1997. La révolution agricole médiévale: discussion. *Études rurales*, 145–46: 51–57.

Dury, G., Lythe, A., Marquez-Grant, N., Garcia-Rubio, A., Graziani, G., Mari, J., et al. 2019. The Islamic Cemetery at 33 Bartomeu Vicent Ramon, Ibiza: Investigating Diet and Mobility Through Light Stable Isotopes in Bone Collagen and Tooth Enamel. *Archaeological and Anthropological Sciences*, 11: 3913–30. https://doi.org/10.1007/s12520-018-0644-4

Dyer, C., Thoen, E. & Williamson, T. 2018. Conclusion: The Rationale of Open

Fields. In: C. Dyer, E. Thoen & T. Williamson, eds. *Peasants and Their Fields* (Comparative Rural History of the North Sea Area 16). Turnhout: Brepols, pp. 257–75. https://doi.org/10.1484/M.CORN-EB.5.114276

Evans, J.A., Chenery, C.A. & 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: 754–64. https://doi.org/10.1039/C2JA10362A

Evans, J., Chenery, C., Mee, K., Cartwright, C.E., Lee, K.A., Marchant, A.P. &. Hannaford, L. 2018. *Biosphere Isotope Domains GB (V1): Interactive Website*. London: British Geological Survey. https://doi.org/10.5285/3b141dce-76fc-4c54-96fa-c232e98010ea

Evans, J.A., Montgomery, J., Wildman, G. & Boulton, N. 2010. Spatial Variations in Biosphere ^{87}Sr/^{86}Sr in Britain. *Journal of the Geological Society*, 167: 1–4. https://doi.org/10.1144/0016-76492009-090

Filipović, D., Meadows, J., Dal Corso, M., Kirleis, W., Alsleben, A., Akeret, Ö., 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: 13698. https://doi.org/10.1038/s41598-020-70495-z

Fuller, B.T., Fuller, J.L., Sage, N.E., Harris, D.A., O'Connell, T.C., Hedges, R.E.M., et al. 2005. Nitrogen Balance and δ^{15}N: Why You're Not What You Eat During Nutritional Stress. *Rapid Communications in Mass Spectrometry*, 19: 2497–506. https://doi.org/10.1002/rcm.2090

Fuller, B.T., Molleson, T.I., Harris, D.A., Gilmour, L.T. & Hedges, R.E.M. 2006. Isotopic Evidence for Breastfeeding and Possible Adult Dietary Differences From Late/Sub-Roman Britain. *American Journal of Physical Anthropology*, 129: 45–54. https://doi.org/10.1002/ajpa.20244

Gannes, L.Z., del Rio, C.M. & 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: 725–37. https://doi.org/10.1016/S1095-6433(98)01016-2

García-Collado, M.I., Ricci, P., Catalán Ramos, R., Altieri, S., Lubritto, C. & Quirós Castillo, J.A. 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: 3765–82. https://doi.org/10.1007/s12520-018-0672-0

Greco, T., Zangrillo, A., Biondi-Zoccai, G. & Landoni, G. 2013. Meta-Analysis: Pitfalls and Hints. *Heart, Lung and Vessels*, 5: 219–25.

Guede, I., Ortega, L.A., Zuluaga, M.C., Alonso-Olazabal, A., Murelaga, X., Pina, M., et al. 2017. Isotope Analyses to Explore Diet and Mobility in a Medieval Muslim Population at Tauste (NE Spain). *PLoS ONE*, 12: e0176572. https://doi.org/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: Article 313. https://doi.org/10.3389/fevo.2019.00313

Hakenbeck, S.E., Evans J., Chapman H. & Fóth, E. 2017. Practising Pastoralism in an Agricultural Environment: An Isotopic Analysis of the Impact of the Hunnic Incursions on Pannonian Populations. *PLoS ONE*, 12: e0173079. https://doi.org/10.1371/journal.pone.0173079

Hamerow, H., Bogaard, A., Charles, M., Forster, E., Holmes, M., McKerracher, 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*, 23: 585–609. https://doi.org/10.1017/eaa.2020.6

Hannah, E.L., McLaughlin, T.R., Keaveney, E.M. & Hakenbeck, S.E. 2018. Anglo-Saxon Diet in the Conversion Period: A Comparative Isotopic Study Using Carbon and Nitrogen. *Journal of Archaeological Science: Reports*, 19: 24–34. https://doi.org/10.1016/j.jasrep.2018.02.012

Haydock, H., Clarke, L., Craig-Atkins, E., Howcroft, R. & Buckberry, J. 2013. Weaning at Anglo-Saxon Raunds: Implications for Changing Breastfeeding Practice in Britain over Two Millennia.

American Journal of Physical Anthropology, 151: 604–12. https://doi.org/10.1002/ajpa.22316

Hedges, R.E.M. 2003. On Bone Collagen–Apatite-Carbonate Isotopic Relationships. *International Journal of Osteoarchaeology*, 13: 66–79. https://doi.org/10.1002/oa.660

Hedges, R.E.M., Clement, J.G., Thomas, C.D.L. & O'Connell, T.C. 2007. Collagen Turnover in the Adult Femoral Mid-Shaft: Modeled from Anthropogenic Radiocarbon Tracer Measurements. *American Journal of Physical Anthropology*, 133: 808–16. https://doi.org/10.1002/ajpa.20598

Hines, J. & Bayliss, A. eds. 2013. *Anglo-Saxon Graves and Grave Goods of the 6th and 7th Centuries AD: A Chronological Framework* (Society for Medieval Archaeology Monograph 33). London: Society for Medieval Archaeology.

Howcroft, R., Eriksson, G. & 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: 217–30. https://doi.org/10.1002/ajpa.22113

Jarman, C.L., Biddle, M., Higham, T. & Bronk Ramsey, C. 2018. The Viking Great Army in England: New Dates from the Repton Charnel. *Antiquity*, 92: 183–99. https://doi.org/10.15184/aqy.2017.196

Jordana, X., Malgosa, A., Casté, B. & Tornro, C. 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: 3751–63. https://doi.org/10.1007/s12520-019-00777-9

Kassambara, A. 2017. *Practical Guide to Cluster Analysis in R: Unsupervised Machine Learning: Volume 1*. Web resource available at: http://www.sthda.com/english/ (Statistical Tools for High-Throughput Data Analysis).

Knapp, Z. 2018. The Zooarchaeology of the Anglo-Saxon Christian Conversion: Lyminge, a Case Study (unpublished PhD dissertation, University of Reading).

Kruschke, J.K. 2013. Bayesian Estimation Supersedes the T Test. *Journal of Experimental Psychology: General*, 142: 573–603. https://doi.org/10.1037/a0029146

Kusaka, S., Uno, K.T., Nakano, T., Nakatsukasa, M. & Cerling, T.E. 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: 300–11. https://doi.org/10.1002/ajpa.22775

Leggett, S. 2021. Migration and Cultural Integration in the Early Medieval Cemetery of Finglesham, Kent, Through Stable Isotopes. *Archaeological and Anthropological Sciences*, 13: 171. https://doi.org/10.1007/s12520-021-01429-7

Leggett, S., Rose, A., Praet, E. & Le Roux, P. 2021. Multi-Tissue and Multi-Isotope (δ^{13}C, δ^{15}N, δ^{18}O and $^{87/86}$Sr) Data for Early Medieval Human and Animal Palaeoecology. *Ecology*, 102: e03349. https://doi.org/10.1002/ecy.3349

Lightfoot, E., Šlaus, M., Rajić Šikanjić, P. & O'Connell, T. 2015. Metals and Millets: Bronze and Iron Age Diet in Inland and Coastal Croatia Seen through Stable Isotope Analysis. *Archaeological and Anthropological Sciences*, 7: 375–36. https://doi.org/10.1007/s12520-014-0194-3

López-Costas, O. & 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: 141–54. https://doi.org/10.1002/ajpa.23016

Lucy, S., Newman, R, Dodwell, N., Hills, C., Dekker, M., O'Connell, T., et al. 2009. The Burial of A Princess? The Later Seventh- Century Cemetery at Westfield Farm, Ely. *The Antiquaries Journal*, 89: 81. https://doi.org/10.1017/S0003581509990102

Mays, S. & 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: 867–74. https://doi.org/10.1016/j.jas.2011.10.013

Müldner, G. 2016. Marine Fish Consumption in Medieval Britain: The Isotope Perspective from Human Skeletal Remains. In: J.H. Barrett & D.C, Orton, eds. *Cod and Herring: The Archaeology and History of Medieval Sea Fishing*. Oxford: Oxbow Books, pp. 239–49.

Murtagh, F. & Legendre, P. 2014. Ward's Hierarchical Agglomerative Clustering Method: Which Algorithms Implement Ward's Criterion? *Journal of Classification*,

31: 274–95. https://doi.org/10.1007/s00357-014-9161-z

O'Connell, T.C. & Hull, B.D. 2011. Diet: Recent Evidence from Analytical Chemical Techniques. In: D.A. Hinton, S. Crawford & H. Hamerow, eds. *The Oxford Handbook of Anglo-Saxon Archaeology*. Oxford: Oxford University Press, pp. 667–87. https://doi.org/10.1093/oxfordhb/9780199212149.013.0034

O'Leary, M.H. 1988. Carbon Isotopes in Photosynthesis. *BioScience*, 38: 328–36. https://doi.org/10.2307/1310735

Orton, D., Morris, J. & 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. https://doi.org/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, R.V. 2015. Food for the Soul: The Dynamics of Fishing and Fish Consumption in Anglo-Saxon England: c. AD 410–1066 (Unpublished PhD dissertation, University of Nottingham).

Richards, M.P., Fuller, B.T. & Molleson, T.I. 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: 122–31. https://doi.org/10.1016/j.jas.2005.07.003

Rizzetto, M., Crabtree, P.J. & 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: 535–56. https://doi.org/10.1017/eaa.2017.13

Robson, H.K., Andersen, S.H., Clarke, L., Craig, O.E., Gron, K.J., Jones, A.K.G., 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: 105–18. https://doi.org/10.1179/1749631415Y.0000000014

RStudio Team 2019. *RStudio: Integrated Development Environment for 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 (Unpublished DPhil dissertation, University of Oxford).

Sayle, K.L., Hamilton W.D., Cook G.T., Ascough, P.L., Gestsdóttir H. & McGovern, T.H. 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: 126–36. https://doi.org/10.1002/ajpa.22939

Serjeantson, D. & Woolgar, C.M. 2006. Fish Consumption in Medieval England. In: C.M. Woolgar, D. Serjeantson & T. Waldron, eds. *Food in Medieval England: Diet and Nutrition*. Oxford: Oxford University Press, pp. 102–30.

Taylor, G.C., Hill, J.M., Jackson, M.C., Peel, R.A. & Weyl O.L.F. 2017. Estimating $\delta^{15}N$ 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, L.L. & Fagre, T. 1993. Effect of Diet Quality and Composition on the Isotopic Composition of Respiratory CO_2, Bone Collagen, Bioapatite, and Soft Tissues. In: J.B. Lambert & G. Grupe, eds. *Prehistoric Human Bone: Archaeology at the Molecular Level*. Berlin/Heidelberg: Springer, pp. 121–55. https://doi.org/10.1007/978-3-662-02894-0_5

van Wely, M. 2014. The Good, the Bad and the Ugly: Meta-Analyses. *Human Reproduction*, 29: 1622–26. https://doi.org/10.1093/humrep/deu127

Vidal-Ronchas, R., Rajić Šikanjić, P., Premužić, Z., Rapan Papeša, A. & Lightfoot, E. 2019. Diet, Sex, and Social Status in the Late Avar Period: Stable Isotope Investigations at Nuštar Cemetery, Croatia. *Archaeological and Anthropological Sciences*, 11: 1727–37 https://doi.org/10.1007/s12520-018-0628-4

Ward, J.H. 1963. Hierarchical Grouping to Optimize an Objective Function. *Journal of the American Statistical Association*, 58: 236–44. https://doi.org/10.2307/2282967

Weller, D.L. & 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: 57–73. https://doi.org/10.1080/03670244.2014.922071

Whitelock, D. 1996. The Laws of Wihtred, King of Kent (695). In: D. Whitelock, ed. *English Historical Documents Volume I, c. 500–1042* (2nd ed. 1979 reissued 1996). London, New York: Routledge, pp. 396–99.

Zhu, M. & 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: 145–53. https://doi.org/10.1002/ajpa.23731

Zuur, A.F., Ieno, E.N. & Elphick C.S. 2010. A Protocol for Data Exploration to Avoid Common Statistical Problems. *Methods in Ecology and Evolution*, 1: 3–14. https://doi.org/10.1111/j.2041-210X.2009.00001.x

BIOGRAPHICAL NOTES

Sam Leggett is currently a Leverhulme Early Career Fellow at the University of Edinburgh. She specializes in early medieval and biomolecular archaeology, and is interested in human–environment interactions, foodways, migration, and cross-cultural contact in the first millennium AD.

Address: School of History, Classic and Archaeology, William Robertson Wing, Teviot Place, Edinburgh EH8 9AG, UK. [email: sam.leggett@ed.ac.uk]. ORCiD: 0000-0001-6259-1457

Une approche méta-analytique hiérarchique pour appréhender l'évolution de l'alimentation au cours du premier millénaire apr. J.-C. en Europe occidentale

Un grand nombre de changements dans le milieu socio-environnemental se reflète dans la documentation archéologique et paléoécologique du premier millénaire apr. J.-C. en Europe. Sur la base d'indications publiées et de nouvelles données isotopiques provenant d'Europe occidentale, l'auteur de cet article examine comment l'utilisation des denrées alimentaires s'est transformée entre environ 350 et 1200 apr. J.-C. ; elle identifie l'aire de distribution du millet, évalue l'importance d'une consommation de ressources marines et compare les différences régionales entre l'alimentation des enfants et des adultes. Elle met l'accent sur les interactions culturelles à grande échelle et traite l'Angleterre du haut Moyen Âge dans une étude de cas approfondie. Elle remet en cause la consommation des ressources marines en Angleterre après le « Fish Event Horizon » et examine les changements perceptibles dans les pratiques agricoles, l'influence de la christianisation, et le rôle des poissons d'eau douce dans l'alimentation. Son approche méta-analytique hiérarchique lui permet d'explorer les relations entre humains et leur environnement et de déceler des conséquences importantes pour l'alimentation en Europe durant le premier millénaire apr. J.-C. Translation by Madeleine Hummler

Mots-clés: Haut Moyen Âge, isotopes, nutrition, alimentation, identité, apprentissage automatique

Ein hierarchischer, meta-analytischer Ansatz zur Frage der wechselnden Ernährung in Westeuropa im ersten Jahrtausend n. Chr

Die archäologischen und paläo-ökologischen Angaben des ersten Jahrtausend n. Chr. widerspiegeln erhebliche Veränderungen in der sozialen und umweltlichen Gestaltung Europas. Auf der Basis von veröffentlichen und neu erarbeiteten Daten aus Westeuropa untersucht die Verfasserin, wie sich die Ressourcennutzung zwischen ca. 350 und 1200 n. Chr. verändert hat. Die Verbreitung von Hirse und

der Verbrauch von wesentlichen Meeresressourcen werden bestimmt und die Ernährung von Kindern und Erwachsenen werden regional verglichen. Interkulturelle Beziehungen auf einer breiten Ebene werden herausgehoben und eine ausführliche Fallstudie betrifft England im Frühmittelalter. Die Aufnahme von Meeresressourcen nach dem „ Fish Event Horizon" wird bezweifelt und die Veränderungen in der Landwirtschaft, der Einfluss der Christianisierung und die Rolle vom Süßwasserfisch in der Ernährung werden untersucht. Die Anwendung einer hierarchischen, meta-analytischen Methode erlaubt der Verfasserin, Interaktionen zwischen Mensch und Umwelt zu bestimmen und bedeutende Auswirkungen auf wechselnde Ernährungsweisen im ersten Jahrtausend n. Chr. in Europa zu erkennen. Translation by Madeleine Hummler

Stichworte: Frühmittelalter, Isotopen, Nahrung, Ernährungsweise, Identität, maschinelles Lernen