‘Tell me what you eat, and I will tell you who you are’

A Multi-Tissue and Multi-Scalar Isotopic Study of Diet and Mobility in Early Medieval England and its European Neighbours

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This dissertation is submitted for the degree of Doctor of Philosophy
Preface

This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text.

It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text.

It does not exceed the prescribed word limit of 80,000 words for the Archaeology and Anthropology Degree Committee.

I declare here and in Chapter 4 that parts of the laboratory work for this thesis were completed in collaboration with Alice Rose, PhD candidate on the After the Plague Project (Department of Archaeology, Cambridge), and with Estelle Praet (2019, MPhil student, Department of Archaeology, Cambridge) under my supervision. For full details see Chapter 4.
Summary

This thesis is concerned with the impact of socio-economic, political and environmental shifts on Early Medieval communities, specifically England and its links with continental Europe. I have utilised multi-tissue (bone, dentine and enamel), multi-isotope ($\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$ and $^{87/86}Sr$) and multi-proxy data to analyse the lifeways of people in Early Medieval England within a European context in a multi-scalar way (sub-continental, regional, kingdom and community scales). This meta-analytical approach has allowed me to investigate Early Medieval transitions across the first millennium AD and better characterise and disentangle human-environment interactions in the period. Throughout this thesis high levels of isotopic variability and cultural dynamism within Early Medieval communities are clear. The core themes of this work are – climate and environment, changing foodways and migration.

This approach has allowed me to better provenance people based on isotopic diversity and see cross-cultural contact. It also highlights the impact of climate change (the Late Antique Little Ice Age and Medieval Warm Period) on human $\delta^{18}O$ values, showing the widespread and relatively rapid impact these events had on climate and on drinking water sources.

The significant diachronic changes in both diet and in mobility patterns found here reflect the highly dynamic and far from insular position of England within Europe in the first millennium AD. My analyses support a model of continual and relatively large-scale migration from the continent Europe across the period, and changes to foodways which reflect not just shifts in economics and agricultural practice but changing worldviews (e.g. the impacts of Christianisation).

Isotopic data when combined with archaeo-historical evidence show that identity construction in Early Medieval communities was highly complex, and there is no clear link between isotopic patterns, genetics and grave goods usually seen as “ethnic” signifiers. I show that these were multi-origin communities in continual contact through long-distance networks which influenced the changes we see throughout the first millennium AD.

Samantha A. Leggett
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<tr>
<td>ADNA</td>
<td>Ancient DNA</td>
</tr>
<tr>
<td>AIR/NAIR</td>
<td>Air - used as a standard for reporting nitrogen stable isotope abundance</td>
</tr>
<tr>
<td>ALT</td>
<td>Altitude</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance statistical test</td>
</tr>
<tr>
<td>ASA</td>
<td>American Statistical Association</td>
</tr>
<tr>
<td>ASC</td>
<td>Anglo-Saxon Chronicle</td>
</tr>
<tr>
<td>BAR</td>
<td>British Archaeological Reports</td>
</tr>
<tr>
<td>BEST</td>
<td>Bayesian Estimation Supersedes the T test</td>
</tr>
<tr>
<td>BGS</td>
<td>British Geological Survey</td>
</tr>
<tr>
<td>CAM</td>
<td>Crassulacean Acid Metabolism (type of photosynthetic pathway in plants usually found in desert environments e.g. cacti and succulents)</td>
</tr>
<tr>
<td>CAU</td>
<td>Cambridge Archaeological Unit</td>
</tr>
<tr>
<td>CBA</td>
<td>Council for British Archaeology</td>
</tr>
<tr>
<td>CCC</td>
<td>Cubic Clustering Criterion or CCC index for optimal number of clusters</td>
</tr>
<tr>
<td>DDC</td>
<td>Detecting Deviating Cells algorithm</td>
</tr>
<tr>
<td>DW</td>
<td>Drinking Water</td>
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<tr>
<td>EDA</td>
<td>Exploratory Data Analysis</td>
</tr>
<tr>
<td>EHESS</td>
<td>École des hautes études en sciences sociales</td>
</tr>
<tr>
<td>EMC</td>
<td>Elemental Microanalysis Caffeine laboratory standard</td>
</tr>
<tr>
<td>ENGLAID</td>
<td>English Landscape and Identities Project</td>
</tr>
<tr>
<td>FEEDSAX</td>
<td>Feeding Anglo-Saxon England Project</td>
</tr>
<tr>
<td>FEH</td>
<td>Fish Event Horizon</td>
</tr>
<tr>
<td>FMASS</td>
<td>A Forum for Multidisciplinary Anglo-Saxon Studies</td>
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<tr>
<td>GMWL</td>
<td>Global Meteoric Water Line</td>
</tr>
<tr>
<td>GSI</td>
<td>Geological Survey of Ireland</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphic User Interface</td>
</tr>
<tr>
<td>HE</td>
<td>Bede's <em>Historia Ecclesiastica Gentis Anglorum</em></td>
</tr>
<tr>
<td>IA/SIA</td>
<td>isotope analysis/stable isotope analysis or analyses</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>ICMS</td>
<td>Ion Chromatography Mass Spectrometry</td>
</tr>
<tr>
<td>IQR</td>
<td>Interquartile Range</td>
</tr>
<tr>
<td>ISAS</td>
<td>International Society of Anglo-Saxonists</td>
</tr>
<tr>
<td>ISSEME</td>
<td>International Society for the Study of Early Medieval England</td>
</tr>
<tr>
<td>LALIA</td>
<td>Late Antique Little Ice Age</td>
</tr>
<tr>
<td>LMWL</td>
<td>Local Meteoric Water Line</td>
</tr>
<tr>
<td>M1</td>
<td>First molar</td>
</tr>
<tr>
<td>M2</td>
<td>Second molar</td>
</tr>
<tr>
<td>M3</td>
<td>Third molar</td>
</tr>
<tr>
<td>MAP</td>
<td>Modelled Annual Precipitation</td>
</tr>
<tr>
<td>MCMC</td>
<td>Markov Chain Monte-Carlo</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
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<tr>
<td>MDM</td>
<td>Mean of the Difference of the Means</td>
</tr>
<tr>
<td>MDSTDEV</td>
<td>Mean of the Difference of the Standard Deviations</td>
</tr>
<tr>
<td>MEH</td>
<td>Meat Event Horizon</td>
</tr>
<tr>
<td>MNI</td>
<td>Minimum Number of Individuals</td>
</tr>
<tr>
<td>MOLA</td>
<td>Museum of London Archaeology</td>
</tr>
<tr>
<td>MWP</td>
<td>Medieval Warm Period (otherwise known as Medieval Climate Anomaly, Medieval Climatic Optimum or Medieval Warm Epoch)</td>
</tr>
<tr>
<td>NGU</td>
<td>Norges Geologiske Undersøkelse (Geological Survey of Norway)</td>
</tr>
<tr>
<td>OIPC</td>
<td>Online Isotopes in Precipitation Calculator</td>
</tr>
<tr>
<td>OMA</td>
<td>Oxygen [Isotopes] Map Annual</td>
</tr>
<tr>
<td>PCTE</td>
<td>Polycarbonate Track-etched</td>
</tr>
<tr>
<td>PDB/VPDB</td>
<td>[Vienna] Pee Dee Belemnite laboratory standard</td>
</tr>
<tr>
<td>PM2</td>
<td>Second premolar</td>
</tr>
<tr>
<td>PPD</td>
<td>Posterior Predictive Distribution</td>
</tr>
<tr>
<td>QQPLOT</td>
<td>Quantile-Quantile Plot for graphically testing distributions for normality</td>
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<tr>
<td>SIMM</td>
<td>Stable Isotope Mixing Model</td>
</tr>
<tr>
<td>SMOW/VSMOW</td>
<td>[Vienna] Standard Mean Ocean Water laboratory standard</td>
</tr>
<tr>
<td>SOP</td>
<td>Standard Operating Procedure</td>
</tr>
<tr>
<td>UML</td>
<td>Unsupervised Machine Learning</td>
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1 Introduction and Research Rationale

“Tell me what you eat, and I will tell you what you are”
– Jean Anthelme Brillat-Savarin

1.1 Brief introduction
The Early Medieval period was a time of great dynamism with people, objects and ideas all in a state of flux and movement across Europe. It is a period where identities are visible at different scales, both during the period and with far reaching implications for the present. When considering how identities were formed and re-formed in the past, perhaps no actions are so intimate and acts of identity formation as the choices of the food we eat and how we bury the dead.

This thesis tackles issues of transition, movement and identity by studying the people buried in Early Medieval cemeteries, using their skeletons to tell the story of their environment and their role in it – where they grew up, what they ate, who they may have been, how their community chose to lay them to rest and what this can tell us about their society.

As Jean Anthelme Brillat-Savarin so aptly summarised – food is an integral part of identity both personal and cultural. Food, environment and identity are intrinsically linked. Food is a reflection of the environment, and when it is transformed into cuisine it also carries cultural memory and meaning within it. Therefore, isotopic signatures from biological tissues are an imprint of foodways and the environment (DeNiro, 1985; Hedges and Reynard, 2007; Mallet, 2016: 1), with the implications for cuisine another aspect from isotopic signatures impacting the performance of identity.

Everyone has to eat and drink, and so in archaeology consumption is central – 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 (Borowski, 2004; Cook, 2008; Vallianatos and Raine, 2008; Weller and Turkon, 2015). During the period of study here, c. 450-1100 AD there is a lot of movement of people, ideas and goods, and cultural change (religious, economic, political etc.) throughout Europe, and this is to greater and lesser extents are visible in the archaeological record. Biomolecular archaeology gives us a unique toolkit for studying foodways, mobility and bodies and the context in which these bodies lived, from the individual to larger populations, in a way which other forms of archaeology and history cannot. Isotopic analyses use the chemical memories of past events stored in the tissues of the dead to inform us about their lives. They are indicators of migration, and, combined with the other archaeological evidence, can also serve as an indicator of cultural integration within Early Medieval communities. The biochemical indicators of diet give us not only nutritional information but also tell us about resource exploitation, agriculture, economy and ultimately about foodways and identity.

This thesis is the first integrated multi-scalar, multi-tissue, multi-isotope and multi-proxy analysis for Early Medieval England and parts of western Europe. There have been smaller scale or more focused assessments of isotopic data but none at this scale using such multi-proxy evidence. Ultimately, I am interested in (re)imagining everyday life in Early Medieval England (c. 450-1100 AD) by utilising isotopic data alongside archaeo-historical evidence. This chapter deals with the rationale for this research, its questions and aims, the boundaries of the study (geographical and chronological) and the overall thesis structure.

1.2 Why study diet and mobility in the Early Middle Ages?

Studying diet and mobility using isotope analyses (IAs) allows us to look at the complex relationships between aspects of everyday life, ritual, economics and identities together with ecology. This is precisely what is needed to tackle key questions and long-standing debates about the Early Middles Ages.

The study of food and consumption in the past and all that comes with that (nutrition, foodways, cookery...) gives us insight into an aspect of daily life which is so imbued with meaning and ritual. We can learn so much about agriculture,
economics, food preferences, social structure and even religion from the study of food.

The study of mobility is also key to understanding how, when and where people moved from and to and perhaps even why during this period of fluidity. Better knowledge of mobility and migration can give insight into practices such as exogamy, community structure and integration, political allegiances and cross-cultural contact. Given some of the major Early Medieval shifts I outline below, studying human mobility can also tell us how people reacted and adapted to these socio-environmental transitions (Baker and Tsuda, 2015). These migration events, if they did occur, are hotly contested in archaeology and history with significant consequences for modern nationalist myths and political ideologies. The nature of these transitions and some of the key scholarship surrounding them will be summarised below.

1.2.1 Early Medieval transitions
The core of this work is about transitions. From the fourth/fifth century AD onwards, England and its neighbours saw several major cultural and socio-economic shifts as well as huge environmental changes and pandemics. At a European scale, the decline of the western Roman Empire is my starting point. The Romanisation of Britain, and subsequent decline of Roman influence caused changes in local and regional governance, taxation, networks of trade and communication, as well as in settlement structure and farming and other aspects of everyday life (Blair, 2000: xiii, 2003: 1–5; Stenton, 1971: 1–16).

Major environmental changes, epidemics and pandemics also had severe impacts on the population of Late Antique and Early Medieval Europe. Part way through our period the ‘Late Antique Little Ice Age’ (LALIA) occurred, which was a period of cooling lasting from approximately 536 to 660AD, with the coldest century for 2000 years. It was caused by several large volcanic eruptions (Büntgen et al., 2016, 2017; Di Cosmo et al., 2017; Fei et al., 2007; Helama et al., 2017; Loveluck et al., 2018; Luterbacher et al., 2016). The end of our period is marked by the so called ‘Fish Event Horizon’ (FEH) but also by the ‘Medieval Climate Anomaly’ or ‘Medieval
Warm Period’ (MWP) c. 950-1250 AD, which was followed by the ‘Little Ice Age’ from 1400-1700 AD (Lamb, 1965; Loveluck et al., 2018; Mann et al., 2009).

Plague hit Europe not long after the onset of LALIA and the combined effects of climate change and plague are often used to explain the acceleration of the decline of many Late Antique regimes although this is very much debated (Alt et al., 2014; Büntgen et al., 2016; Di Cosmo et al., 2017). According to historical sources, the Plague of Justinian wiped out much of the population of the Eastern Mediterranean, and the rest of Europe with mortality estimates between 25-60%, making it potentially as deadly as the Black Death, although this too is contested (Harbeck et al., 2013; Keller et al., 2019; Mordechai et al., 2019; Wagner et al., 2014). In terms of direct evidence for plague in Early Medieval England a recent study including Edix Hill (one of the sites I analysed in collaboration with the After the Plague Project) identified four individuals with Y. pestis DNA, with the possibility of more positive identifications to be announced soon (Keller et al. 2019, Scheib pers comm). It is therefore not surprising that there were major cultural and socio-economic changes during this period, namely changes in burial practice and grave goods, farming practices and trade, although the relationships between all factors is highly complex.

This period is also marked by three major historically attested migration events to England, the earliest of which is often termed the “Adventus Saxonum” (or ‘coming of the Saxons’) which is a part of the larger European “Migration Period” (Hills, 2013b, 2015; Michelet, 2017). The next is the Scandinavian settlements and the establishment of the Danelaw in England, and finally the Norman Conquest of 1066 AD.

These migration events are hotly contested and the “Adventus” in particular has been the source of debate for over a century. There is a pendulum of discussion which with new evidence and thinking swings between elite replacement models with top-down cultural change and large-scale migration over several generations (Hamerow, 1997; Härke, 2003, 2004, 2011; Hills, 2013a, 2013b, 2015; Pattison, 2008; Thomas et al., 2006, 2008). The “Adventus” theoretically occurred at the end
of the Roman occupation in Britain in the fifth century AD and resulted in large material-cultural changes in England. The main historical sources for this migration are Bede, Gildas and the Anglo-Saxon Chronicle which all state that groups of people migrated from parts of what is now the Netherlands, northern Germany and the Jutland peninsula to Britain (Gildas, 2010; The Venerable Bede, 2009; Unknown, 2008).1 The tension between the archaeological and genetic evidence and the social interpretations for this migration evidence will be highlighted in my brief literature review below, but I hope with this work to go some way to answering the question of the scale of any migration.

The second major migration event of interest in this thesis is the Viking incursions and subsequent settlements. These began in earnest in the mid-ninth century AD and continued arguably right up until the Norman Conquest (Blair, 2000: 39–75; Buckberry et al., 2014; Richards, 2005: 63–76; Stenton, 1971: 239–269, 320–364, 394–436, 502–525). In contemporary sources the “Danelaw” area of England was certainly seen as markedly different in law and customs to the “English” kingdoms (Blair, 2000: 39–75; Hadley, 2006; Hall, 2000; Richards, 2005: 63–76; Stenton, 1971: 502–525). It is clear from the archaeology that there were changes in land management, settlements, material culture and aspects of diet (Barrett, 2003; Barrett et al., 2001; Buckberry et al., 2014; Hadley, 2000, 2006; Hadley and Richards, 2000; Trafford, 2000).

However, the concerns over the nature of these settlements remain largely the same as for the “Adventus Saxonum” – the scale of migration and the nature of cross-cultural interaction/integration, and how to reconcile the various narratives and lines of evidence (Buckberry et al., 2014; Evison, 2000; Hadley, 2017; Hadley and Richards, 2000; Innes, 2000; Montgomery et al., 2014; Trafford, 2000).

And finally, the last major invasion/migration event of the period is the Norman Conquest which began in 1066 AD and is a historically well-attested elite-

1 It is important to note here that these sources whilst medieval are not contemporary with the events they describe, the closest is Gildas (c. sixth century) and then Bede’s HE which post-dates the migrations by c. 300 years (written c. 731 AD).
replacement invasion. The various lines of evidence all suggest this was not a large-scale migration of people from northern France, but instead military personnel and Norman elites who followed William the Conqueror and were rewarded with land. The subsequent settlement changes change in language, cuisine and other cultural shifts were supposedly due to top-down influence rather than a large-scale population replacement (Baeten et al., 2013; Craig-Atkins, 2017; Daniell, 2003; Garnett, 2009; Holt, 1982; Jervis, 2013; Jervis et al., 2016, 2017; Loyn, 1991; Sykes, 2007; Sykes et al., 2016; Sykes and Carden, 2011). Mobility and migrants are the main foci of my study of mobility in Chapter 6.

Migrations not only had an impact on the cultural landscape of Britain, but the re-introduction of Christianity to the island had wide-ranging implications for more than just the religious landscape of Britain. The adoption of Christianity had political and economic implications. I am interested in how this may have affected diet (through religious dietary laws, as well as trade relationships within “Christendom”) and the changes this brought about in funerary practices which allow me to investigate orthopraxy through the archaeological record (Barrett, 2003; Brownlee, 2019; Dunn, 2010; Geake, 2002; Hannah et al., 2018; Knapp, 2018; Leggett, 2016, 2017; Lucy, 2000; Petts, 2011; Reynolds, 2015; Whitelock, 1994).

Christianity was not the only potential change to Early Medieval diet in England. Christianisation is one part of larger-scale economic shifts during this period which saw changes to trade especially around the North Sea zone and the rise of the wics/emporia after c. 700AD (Astill, 2011; Campbell, 2004; Hill and Cowie, 2001; Loveluck and Tys, 2006; Pestell, 2011). These new trading centres in turn seem to be closely linked to changes in currency, and we see shifts in settlement across England with settlement nucleation and urbanism on the rise across the period (Astill, 2011; Blair, 2018; Crabtree, 2018; Hamerow, 1991, 2002, 2012; Leggett, 2016; Loveluck et al., 2018; Roberts and Wrathmell, 2000; Speed, 2013).

This is followed by the so-called “agricultural revolution” between the ninth and thirteenth centuries AD which had three major innovations – changes to plough technology, most notably the mould-board plough, two-and-three field crop
rotation and changes to crop regimes which meant less need for manure (Banham and Faith, 2014b; Dyer et al., 2018; Hamerow et al., 2019, 2020; Thomas et al., 2016). This period saw an increase in cereal production, and changes to the types and quantities of crops alongside the agricultural innovations which supported the growing urban communities and facilitated changing power structures (Banham and Faith, 2014c; Duby, 1997; Dyer et al., 2018; Hamerow et al., 2019, 2020). One aspect of these changes appears to be a growing demand for and production of ale. This has implications not just for cereal production and nutrition, but also trade implications with tensions between local non-hopped ales and the hopped ales on the continent, and possibly also for oxygen stable isotope values (Behre, 1999; Brettell, Montgomery, et al., 2012; Hornsey, 2003; Jennings et al., 2005; Unger, 2013).

Another key dietary shift is the “Fish Event Horizon” (FEH) which is evident in the zooarchaeology of Europe around 1000 AD. 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 reasons (Barrett, 2016; Barrett et al., 2004a, 2004b, 2011; Orton et al., 2017; Reynolds, 2015; Serjeantson and Woolgar, 2006). Such a major shift to marine resources should be evident in the human isotopic data as well as the zooarchaeology but has not been well-studied with a large dataset, which is why it is a focal point for my research (Barrett, 2016; Müldner, 2016; Müldner and Richards, 2007; Reynolds, 2015). The major works around the FEH will be briefly summarised below.

1.2.2 A brief history of studying diet and mobility in Early Medieval England

Whilst diet and mobility in Early Medieval England have been the subject of scholarship for some time, few studies discuss both issues together in an integrative and multi-disciplinary way. Therefore, this thesis fills a gap in the literature, synthesising and analysing the isotopic data not just for England but also for large parts of contemporary Europe, so as to better understand the ecology, economy and culture around food during the period, but also the interaction between diet and mobility – foodways and identities. Below I outline major works
on diet and mobility in Early Medieval England, and some key works which look across Europe.

1.2.2.1 Diet

In terms of diet, the works of Ann Hagen and Debby Banham are seminal texts which draw together the textual evidence and archaeology (largely archaeobotany and zooarchaeology) to form a very comprehensive picture of what food was available at which times of year, how these foods were produced and, to a lesser degree, how they were consumed (Banham, 1990, 2004; Hagen, 2006). These are my main sources for the kinds of food and drink available in Early Medieval England. From a literary and cultural perspective “Food Eating and Identity in Early Medieval England” is also useful (Frantzen, 2014). The works of Christopher Woolgar are also useful contextualisation for our period, providing detailed accounts of food and consumption post-1200 AD but also looking at how these foodways developed from earlier trends (Woolgar, 2016; Woolgar et al., 2006).

For understanding agricultural practices and production, in addition to the texts above, the major synthetic work by Banham and Faith “Anglo-Saxon Farms and Farming” details in two parts the crops and animals farmed in Early Medieval England and the practices used to do so, as well as how arable farming played out in different environments through landscape case studies (Banham and Faith, 2014a). Our understanding of animal husbandry in this period is almost entirely due to the works of Pam Crabtree. She details the changes from the Roman to the Early Medieval period in England but also how contact with continental European neighbours influenced agriculture and meat consumption across the Channel, and the other economic and companion uses of animals in the first millennium, largely focusing on East Anglia (Crabtree, 1989, 1996, 2010, 2012, 2014, 2015; Rizzetto et al., 2017).

Zoe Knapp’s doctoral research is a key, in-depth case study of Lyminge, a high-status site in Kent, tracking changes in consumption and animal husbandry through Christianisation. Her work will be discussed in more detail in Chapter 8 (Knapp, 2018). The works of Matilda Holmes are also key zooarchaeological studies for
post-Roman England which integrate animals into the social framework of Early Medieval England and considers identity, foodways as well as economics in her assessment of faunal assemblages (Hamerow et al., 2020; Holmes, 2014a, 2014b, 2016, 2018; Thomas et al., 2013, 2018).

Naomi Sykes’ work has revolutionised our understanding of wild game exploitation in the Middle Ages, especially deer, and highlight change in faunal assemblages, especially across the Norman Conquest, with significant changes to foodways (Lauritsen et al., 2018; Loog et al., 2017; Sykes, 2007, 2010, 2017; Sykes et al., 2016; Sykes and Carden, 2011).

As already mentioned above, the FEH is intrinsically tied to the socio-environmental transitions I investigate in this thesis – climate change, Christianisation, Scandinavian settlement and other cross-cultural contact and trade around the North Sea zone. The key works on the FEH are by James Barrett and include zooarchaeology, genetic and stable isotope studies to look at the causes, mechanisms and implications of this major shift in economy and consumption (Barrett, 2003, 2016; Barrett et al., 2001, 2004a, 2004b, 2008, 2011; Barrett and Orton, 2016). A recent study of the fish bone assemblages for London highlight the key chronological aspects of the FEH. There was an increase in freshwater species around the seventh century with the peak in marine species occurring just before the turn of the millennium. We cannot extrapolate for all of the region based on London, but the evidence is compelling (Orton et al., 2017). Rebecca Reynolds and Zoe Knapp have found that the FEH may have its beginnings earlier in parts of England due to the influence of Christian fasting and dietary laws, and this lends evidence to the duality of the FEH, where freshwater resources may have has a different trajectory to marine resources in Medieval England (Knapp, 2018; Reynolds, 2015).

Sadly, due to issues with preservation there is not a great deal of work on Early Medieval archaeobotany in England, however the works by Mark McKerracher and the FeedSax project have advanced our knowledge of cereal crops and weed ecology in the period considerably (Feeding Anglo-Saxon England, 2019; Hamerow
et al., 2019, 2020; McKerracher, 2014, 2016a, 2016b, 2018, 2019). For instance, McKerracher’s use of charred plant materials has been key in disproving the ‘bread wheat hypothesis’ and has shown that far from coming to dominate the archaeobotany, bread wheat was instead part of a larger expansion of cereal varieties during ‘the long eighth century’ (McKerracher, 2016a). So far there is only one very small study of plant isotopic signatures from Early Medieval England; it shows differences between cereal species and changes to isotopic values in species through time which may be related to agricultural extensification (Hamerow et al., 2020).

The works of Helena Hamerow tie much of the discourse around settlements and agrarian production together, bringing the zooarchaeological and archaeobotanical evidence into the context of settlements and economy (Hamerow, 1991, 2002, 2012; Hamerow et al., 2019). This contextualisation is key to understanding local lived experiences and foodways amidst larger-scale socio-economic shifts.

Another emerging line of evidence is residue analysis on Early Medieval pottery; however, to my knowledge, there are only six studies (four from the same site) published to date for England (Baeten et al., 2013; Charters et al., 1993, 1995; Craig-Atkins et al., 2020; Dunne et al., 2019, 2020). These are the closest we can get to better understanding cookery and recipes for the period. These studies do not necessarily reveal anything surprising but show evidence for mixing of food sources for meals (meat, fish, vegetables) as well as some pottery types being used for specialised storage and cookery.

The promise of proteomics especially from human dental calculus is exciting (Hendy et al., 2018; Jersie-Christensen et al., 2018; Radini et al., 2019; Warinner et al., 2015). DNA of the person whose teeth are being analysed, the foods they ate, and their microbiota can also be recovered from calculus which adds even more

2 Craig-Atkins et al. (2020) and Dunne et al. (2020) are extremely recent and important studies looking at residues in Early Medieval pottery, and in the case of Craig-Atkins et al. also using multi-proxy evidence for changing foodways and cuisine as a result of the Norman Conquest (residues, pottery, zooarchaeology...). These studies came out in the final stages of writing and editing for this thesis so were not able to be fully incorporated in this study but present new and exciting data.
vital information to health, diet and mobility in the past. There is some work forthcoming from Early Medieval sites in south Cambridgeshire, which may indicate that there are differences in social status and the consumption of milk of different species, but the work is preliminary (Scheib, pers comm). I hope that in the future this line of evidence will add significantly to our understanding of diet and mobility in the Early Middle Ages.

In terms of the isotopic evidence for diet, there are a multitude of studies which have used stable isotope analyses for the Early Middle Ages, not just in Britain but across Europe. These tend to be site specific, and as my databases (see digital appendices) show these are often limited in sample size. The first landmark study for Early Medieval England was the diachronic study of the diets of people from York by Gundula Müldner which showed changes in diet from the Roman to later Medieval period (Müldner, 2005; Müldner and Richards, 2007). Müldner has highlighted the ephemerality of the FEH in human tissues before the later Middle Ages and the need for more research into the phenomena using human tissues which this thesis addresses (Buckberry et al., 2014; Müldner, 2016).

Bradley Hull’s doctoral thesis is the largest primary isotopic study of Early Medieval diet in England up to the seventh/eighth century AD, utilising both human and faunal bone. He focussed on sites in East Anglia and Wessex, analysing 410 human bone samples and 344 faunal bones. Hull noticed diachronic change, particularly a shift to more negative $\delta^{13}$C values towards the end of his study period which he thought may be due to increased consumption of domestic fowl or changes to cereal crops, and dismissed any fish consumption as the cause (marine or freshwater) due to a lack of fish bones available at the time (Hull, 2007; O’Connell and Hull, 2011).

There have also been several intensive studies on childhood health – breastfeeding and weaning in Early Medieval England which highlights the osteological paradox which is especially apparent in children, and the isotopic differences in tissues across age groups (Beaumont et al., 2018; Haydock et al., 2013; Macpherson, 2005).
The first synthetic multi-regional isotopic studies of Early Medieval diet came with the “Anglo-Saxon Chronology Project” and its radiocarbon dating programme. As such the burials analysed are of particular typological interest to the project, but they are geographically widely distributed and only a few burials from the same site are analysed (Bayliss et al., 2013; Beavan et al., 2011; Beavan and Mays, 2013; Mays and Beavan, 2012). However, they form an important foundation for this work, especially as they tend to have associated 14C dates which aids chronological frameworks for both dietary change and mobility here.

However, the first truly large-scale synthetic work on dietary isotopes in England was recently completed by Sarah Mallet as part of the EngLAID project. Her work focuses on dietary isotopic change in human and animal bone over the long durée of the Bronze and Iron Ages through to the Norman Conquest (Gosden, 2016; Mallet, 2016; Stansbie and Mallet, 2015). Due to the limitations of Mallet’s database and the broader scale changes the project was focussed on, much of her work had to be redone as there were no individual identification numbers given in the database for skeletons to allow for the collation of contextual data or cross-referencing with the original studies. Mallet’s major conclusions were that there were no significant changes in subsistence from the Iron Age to the eleventh century, but that there are regional differences and subtle changes over time (Mallet, 2016).

1.2.2.2 Mobility

Mobility during the first millennium AD across Europe is both well attested and highly contested. The lines of evidence are now broadening with more genetic studies (both modern and ancient DNA) and stable isotope data now available to integrate with the archaeological and written sources. Most of the studies of mobility in Early Medieval England have been site specific studies focussing on the identification of outliers within the group, occasionally comparing data to a baseline or other sites for context. I will not cover every study here but the ones with accessible data are incorporated into my databases, and the references can be found therein (see digital appendices). My thesis presents the first large-scale
synthetic study of mobility in Early Medieval England, and also for most of western Europe, incorporating isotope data from a variety of studies.

Before the 1990s study of mobility and migration in Early Medieval England relied heavily on historical sources for the origins and scale of these movements (Bede’s *HE*, Gildas and the *ASC* as mentioned above), and debate over the seemingly immediate and rapid changes to language and material culture seen in the fifth and sixth centuries grew (Hamerow, 1997; Härke, 2003, 2011; Hills, 1993, 2003, 2013b, 2015; Oosthuizen, 2019; Scull, 2012). The debate is well summarised by Catherine Hills (2003) and Helena Hamerow (1997) for the earlier migrations with the works of Heinrich Härke central to the debate; and for the ‘Viking Age’ Dawn Hadley and Jo Buckberry amongst others have highlighted the issues with migration and identity (Buckberry et al., 2014; Evison, 2000; Hadley, 2017; Hadley and Richards, 2000; Halsall, 2000; Hamerow, 1997; Härke, 2003, 2004, 2011; Hills, 2003, 2013a, 2015; Innes, 2000; Thomas et al., 2006; Trafford, 2000).

Genetic studies have added to the debate with varying degrees of engagement with the archaeology, but far from being a silver bullet for the debate, the limitations of these studies further confound discussions at the moment. Early studies used modern genetic data from contemporary European populations. It is highly problematic to use modern populations as proxies for the past, and one of the key limitations is time-depth because geneticists are not fully able to chronologically resolve potential genetic inputs from the “*Adventus Saxonum*”, the Scandinavian settlements and the Norman Conquest due to their relative proximity in time (Leslie et al., 2015; Olson, 2008; Schiffels et al., 2016; Schiffels and Sayer, 2017; Winney et al., 2012). Recent aDNA studies have better resolution and can look at familial relationships and ancestry within the ancient populations we wish to know about. Currently data from Early Medieval skeletons is still very limited, although they do show a mixture of “local” Romano-British and northern European lineages in Early Medieval cemeteries in England, with no distinction in terms of funerary treatment (Martiniano et al., 2016; Schiffels et al., 2016; Schiffels and Sayer, 2017). A new pre-print article on “Viking Age” ancient genomes also highlights a high degree of migration and intermarriage across Early Medieval Europe (Margaryan et
This is in stark contrast to earlier work by Mark Thomas and Heinrich Härke who favour models of ethnic and cultural separation in Early Medieval England. This thesis will demonstrate that this idea of cultural and ethnic separation is unfounded given the available data (Pattison, 2008; Thomas et al., 2006, 2008).

So, the pendulum of debate still swings, but how does the isotopic evidence fit in with the archaeological, documentary and genetic data? Smaller isotopic studies on Early Medieval communities have shown that there was likely a large amount of movement around Europe throughout the first millennium AD but identifying “non-locals” and outliers in datasets still proves difficult (Brettell, Evans, et al., 2012; Evans et al., 2012; Groves et al., 2013; Hakenbeck, 2013; Hemer et al., 2013; Krzewińska et al., 2018).

There has been a heavier focus in north-western Europe on identifying the impact of the “Vikings” and the Scandinavian diaspora than on the earlier “Migration Period” although for central and southern Europe the chronological focus is earlier (Alt et al., 2014; Amorim et al., 2018; Arge, 2014; Barrett et al., 2001; Buckberry et al., 2014; Chenery et al., 2014; Frei and Price, 2012; Hakenbeck et al., 2017, 2017; Knudson et al., 2012; Krzewińska et al., 2018; Margaryan et al., 2019; Montgomery et al., 2014; Naumann et al., 2019; Naumann, Krzewińska, et al., 2014; Pollard et al., 2012; Price et al., 2018, 2019; Ryan et al., 2018; Symonds et al., 2014; Vésteinsson and Gestsdóttir, 2014). However, I argue we need to take a more synthetic and larger-scale approach to better assess any of these events and to identify migration, and a part of this thesis is to demonstrate this approach as a highly valuable one to consider population movements in the earlier Middle Ages in northwest Europe.

A recent study has shown that we need to think more critically about baselines, fractionation and identifying outliers/migrants using oxygen stable isotopes in human bioapatite which many studies still fail to do (Lightfoot and O’Connell, 2016). Isotopic data have the potential to add greater resolution to the debate around Early Medieval migrations and mobility, and by utilising different graphical
and statistical techniques this study aims to do just that (Hakenbeck, 2013; Hills, 2015; Lightfoot and O'Connell, 2016; Ríos Frutos, 2017).

1.3 Research questions and aims
The overarching aim of this thesis is to test if there are isotopically visible changes in diet and mobility within Early Medieval England and study if these are related to documented Early Medieval transitions in a multi-scalar way with reference to parts of western Europe. IA is therefore the ideal approach to pursue this aim, as mentioned above, due to the unique position of these biomolecular signatures for capturing the memory of both environmental variation and human actions in the past and adding to our understanding of life in the Early Medieval period alongside other evidence.

My core research questions are – can we see migration between England and the Continent during the Early Medieval period and do these align with the “Adventus Saxonum”, the “Viking Age” and the Norman Conquest? And what impact (if any) do these migrations and major socio-environmental transitions have on food and diet during the period?

The themes of this thesis can be broadly characterised as:
- Isotopic Variability – environmental, physiological and cultural
- Diachronic Change
- Foodways
- Cross-cultural contact and migration
- Identity

Addressing these questions, aims and themes in a multi-scalar way requires a complex combination of meta-analytical data visualisation and analysis techniques and careful integration of the archaeological and historical evidence. The key to tackling multi-proxy data is to address archaeology as human ecology. I have chosen to do so within a bio-cultural framework (Butzer, 1982; Schutkowski, 2005). Bio-cultural approaches see humans as part of the ecosystems they operate in, and balance the biological aspects and needs of the human body (such as diet
and nutrition) with the complexities of human agency and cultural phenomena (Dufour, 2006; Schutkowski, 2005; Zuckerman and Armelagos, 2011). It is an integrative and synthetic framework, reaching across disciplinary and sub-disciplinary boundaries which makes it unique and powerful for bioarchaeology (Zuckerman and Armelagos, 2011: 15). This has allowed me to analyse and contextualise people within their isoscapes, whilst also considering human actions and socio-cultural change.

1.4 Chronological and Geographical Scope

Chronologically this thesis is taking a “longue durée” approach to the Early Medieval period with the core temporal focus being the fifth to eleventh centuries AD, whilst also taking into account data from the Roman and later Middle Ages as points of comparison and allowing for continuity and lack of clear phasing at some sites. Contextualising the data chronologically also allows for diachronic trends to stand out more clearly at all scales. Chapter 3 details the sub-divisions of time in more detail.

This thesis focuses primarily on the modern geographical limits of England, but also includes legacy data from across Early Medieval Europe. This is done to look at trade, exchange, and mobility of people and food(ways) at a sub-continental scale and ground England within its European context. The comparative data from across (mostly) western Europe is not meant to be exhaustive. Instead, I have made every effort to make it substantive from regions with known contact (direct or indirect) with the islands of Britain and Ireland, and from regions with foodways which we know are substantially different from England (e.g. millet consumption in Croatia) to provide a contrast and benchmark on which to better assess isotopic variability and foodways in other parts of Europe.

As a benchmark for isotopically visible ‘significant’ marine consumption I will be using indicative $\delta^{13}C$ values from the literature, similar to using millet consumption in Croatia mentioned above. Archaeological bone collagen from Greenland Eskimo and people in British Columbia (Canada) assumed to be living off principally marine protein have $\delta^{13}C$ values of approximately $-13\%o$, Mesolithic “hunter-
gatherers” between -12 and -15.5‰, Early Medieval “Viking Age” individuals in Orkney with 29% or higher estimated marine intake have δ¹³C values between -15.4 and -18.4‰ (Barrett and Richards, 2004; Chisholm et al., 1982; Cramp et al., 2014). Whereas Bronze Age “farmers” with limited fishing have values between -18.3 and -22.5‰ and other agricultural C₃ northern European populations have been found to have values around -19.6±1.6‰ (Chisholm et al., 1982; Cramp et al., 2014). Therefore due to δ¹³C value overlap between some populations, and the confounding factors in carbon isotopic fractionation mentioned in the next chapter, a relatively high marine proportion in the diet of >25% is taken as a rough guide here to ensure isotopic visibility of consumption and niche separation, which is estimated to produce δ¹³C values of approximately -18.2‰ or higher (Barrett and Richards, 2004; Chisholm et al., 1982; Cramp et al., 2014; Müldner, 2016).

The terminology for time periods, regions and cultural groups are often problematic and anachronistic. With this in mind, I have used a variety of categories and terms to mitigate some of these problems, which are detailed in Chapter 3. However, I want to briefly address my avoidance of ethnic and racialized terms which have been frequently used in Early Medieval research in the past, particularly “Anglo-Saxon”.

For some time now the use of such terms has been criticised and many archaeologists have moved away from explicit use of these terms in most contexts. The problem in the U.K. is that not only has the term “Anglo-Saxon” and its counterparts (Angle, Saxon, Jute, Mercian etc.) been used to describe material culture, ethnic and political divisions but are also used as a chronological designation with Early, Middle and Late Saxon used regularly throughout the literature (FMASS, 2019; Williams, 2019d, 2020b).

During the course of my doctoral research the debate around the term “Anglo-Saxon” and other ethnic and racialized terms such as “Germanic” has come to the forefront. Both terms have a long and complex history and have frequently been used as part of ethno-national mythmaking and particularly as I finish writing amidst the Black Lives Matter revolution, such terms, their history and
connotations must be, and are in the process of being critically assessed and dismantled. The debate in the field came to a head at two meetings of International Society of Anglo-Saxonists (ISAS, now the International Society for the Study of Early Medieval England – ISSEME) in Honolulu in 2017 and Albuquerque in 2019 (Dockray-Miller, 2017; Medievalists of Color, 2019; Miyashiro, 2017; Natanson, 2019; Remein, 2017; Schuessler, 2019; Wade, 2019). These terms are weaponised by the far and alt-right movements, who mis-use and mis-represent the history and archaeology of the Middle Ages for their own purposes, amongst them the current president of the Unites States and white-supremacy terrorists (Andrew B. R. Elliott, 2017; Devega, 2017; Harland, 2017a, 2017b; Ho, 2017; Kaufman, 2017; Livingstone, 2017; Schuessler, 2019; Sturtevant, 2017). These terms have been integral to colonial ideologies and nation-building myths and are therefore highly problematic on many levels (Andrew B. R. Elliott, 2017; Ellard, 2019; Horsman, 1981; Leggett, 2012; Miyashiro, 2017). Some scholars, British archaeologists and historians in particular, warn against “throwing the baby out with the bathwater” (FMASS, 2019; Pohl, 2018; Williams, 2019a, 2019b, 2019c, 2019d, 2020a, 2020b). However, I believe given the current strong push across the world for equality and de-colonisation, it would be irresponsible for me to actively use such terms here when I feel the arguments, I am making do not need this terminology. Therefore, I have avoided ethnic terms in this thesis, although they are not entirely absent due to engagement with previous research, in particular with chronological frameworks.

1.5 Thesis structure

The research questions set out above will be addressed by the following chapters. Chapter 2 outlines principles and applications of isotopic analyses in archaeology and ecology, focusses on processes involved in isotopic variation, and the formation (and analysis of) the tissues studied in this thesis.

[3] There is of course a far greater intellectual argument about the use of ethnic terminology, especially in the past as we cannot know how people identified themselves, and we cannot assume cultural homogeneity (Curta, 2007, 2011; Diaz-Andreu, 2001; Gillett, 2006; Hadley, 2000: 298–306; Harland, 2017b; Leggett, 2013; Pohl, 2018). This debate is complex, and I cannot do justice to it here, but the above references cover the main points.
Chapter 3 details my study design – the decisions made, and steps taken in gathering legacy data, data standardisation and statistical analyses.

Chapter 4 details the primary isotope analyses I undertook – the sampling strategy, samples collected, laboratory methods, and the quality control and assessment of data from the mass spectrometers.

Chapters 5 to 8 form the core of this thesis. Chapter 5 uses a meta-analytical approach to explore environmental and climatic variation across Early Medieval Europe but also within Early Medieval England. It begins with an assessment of available faunal data at both scales and then gives an overview of the collated human data across all tissues and isotopes – enamel (\(\delta^{13}C_{\text{carb}}, \delta^{18}O, ^{87/86}\text{Sr}\)), bone (\(\delta^{13}C_{\text{coll}}, \delta^{15}N_{\text{coll}}\)) and dentine (\(\delta^{13}C_{\text{coll}}, \delta^{15}N_{\text{coll}}\)). It then describes the regional variation, effects of altitude, latitude and longitude, effects of geology across western Europe and the impact of environment type across western Europe for these tissues and isotopes, before doing the same for variation within England.

Chapter 6 focuses on issues of mobility and migration as well as addressing the impact of climate change and “brewing and stewing” on human enamel \(\delta^{18}O\) values during the Early Middle Ages. It tackles these issues by using cluster analysis and by looking at change over time and space.

Chapter 7 addresses diet in Early Medieval Europe and England through stable isotope analysis, using a similar approach to Chapter 6 with cluster analysis, and temporal and spatial changes. It also looks at diet through the life course by comparing different tissues and investigates sex-based dietary differences.

Chapter 8 uses the contextual analyses of the earlier chapters to look at a case study region – Kent and East Sussex, and one cemetery within that area – Finglesham, to investigate diet and mobility at more localised scales.
Chapter 9 summarises the findings and their implications for life in Early Medieval England, which is done thematically – climate and environment, changing foodways and migration. It also proposes avenues for future research.

Overall, this thesis maintains that construction of identity in Early Medieval communities was highly complex, with no clear link between isotopic patterns, genetics and grave goods usually seen as “ethnic” signifiers. Chronological change both in consumption and migration patterns reflect how connected England was in the first millennium AD. Shifts in foodways during the period reflect changes in economics and agriculture but also changing worldviews (e.g. Christianisation). This is demonstrated through the combination of isotopic analyses with other lines of environmental and archaeological evidence across sub-continental, regional and local scales. These were multi-origin 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.
2 Isotopic Analyses – Principles and Applications

This chapter introduces and summarises the principles of isotopic analyses (IAs) in palaeoecology – covering their definition, uses and the varied ecological and physiological factors which influence stable isotope values in biological tissues. In recent years there has been an increased uptake in the use of IAs to study archaeological material and archaeological questions across a wide variety of time periods, geographical regions and sample types. Chemical techniques are now relatively commonplace in bioarchaeological studies to study diet and mobility in the past. There is a growing trend for multi-tissue and multi-isotope studies at individual and populational levels (Bond et al., 2016; Gregoricka et al., 2017; Lamb et al., 2012; Ryan et al., 2018; Zhu and Sealy, 2019).

There are two basic levels of variation to consider when utilising isotopic analyses in archaeology. First, the underlying environmental variation and plant biochemistry which form the base of the food chain for the people and animals we are studying, and, second, the dietary input of the individuals which influences the stable isotope ratios we measure in their tissues. This chapter will give an overview of the history of using isotopic analyses in archaeology, the variables influencing isotope biochemistry, the technique’s practical and theoretical foundations. Further information about stable isotope mass spectrometry and methodologies used are available in Chapter 4.

2.1 History of isotope analysis in archaeology

IA is not a new technique and has been in use for over four decades for palaeodietary research. The first pioneering papers by Vogel and van der Merwe in 1977 and 1978 used differences in the isotopic compositions of carbon in C3 and C4 plants to look at maize consumption in pre-colonial North America (Brown and Brown, 2011: 79, 82–3; van der Merwe and Vogel, 1978; Vogel and van der Merwe, 1977). Since those studies, researchers used the technique and the principles of isotopic fractionation and variation (see below) to distinguish between terrestrial and marine based diets, as well as between carnivores and herbivores (Brown and Brown, 2011: 82–5). These early studies focussed on identifying macro-scale
dietary transitions but, since then, advances in the method and technology have meant that other aspects of human diet and behaviour (such as migration) are able to be investigated using IA.

The use of IA in archaeology, particularly in the UK, boomed in the 1990s and has seen a large expansion in the number of research institutions with suitable mass spectrometers as well as commercially available services in the last two decades. There has been an increasing emphasis on the Roman and medieval periods in recent years, as outlined in Chapter 1. Early work focused primarily on sites or regions, until the past few years, with the work of Sarah Mallet (2016) leading the way in larger isotope meta-analyses. Multi-tissue and multi-isotope work are becoming increasingly popular, but to make the most of these data there is still more experimental work to be done to understand the underlying biochemical processes in the ecosystems and organisms we study. However, the increasing trend in isotopic research in archaeology and ecology towards modelling and meta-analyses, moving beyond site and regional case studies, is promising and interesting insights are being made with these approaches.

2.2 What are isotopes?
The term isotope was first coined by the doctor, feminist and novelist Margaret Todd in 1913 for the chemist Frederick Soddy to describe his discovery that atoms with different atomic masses exhibited the same number of protons and the same chemical properties (Brown and Brown, 2011: 79; Nagel, 1982; Price and Burton, 2012: 90). The chemical properties of an element are defined by the number of protons, while the physical properties (e.g. mass) are defined by the total number of nucleons (protons and neutrons) in the atomic nucleus. Thus each isotope of an element has a different mass number (Brown and Brown, 2011: 79–81; Hoefs, 2009: 1; Price and Burton, 2012: 90). For example, carbon has the atomic number 6, meaning that it has 6 protons, and the isotope carbon-14 would therefore have 6 protons and 8 neutrons. However, despite these subatomic similarities if studied closely there are small but noticeable differences (aside from mass) between isotopes of the same element that influence how they behave in chemical reactions (Allegre, 2008: 358).
Isotopes of an element can be either stable or radioactive. Radioactive isotopes decay gradually over time and stable isotopes do not (Hoefs, 2009: 1). The different masses of isotopes can be quantified using mass spectrometry. This is what underpins radiocarbon dating and the use of stable isotope analysis in earth sciences, ecology, archaeology and other fields. I am only interested in stable and radiogenic (stable nuclides with unstable isotopic ratios/abundances due to being products of radioactive decay) isotopes and their applications here, not radioactive isotopes.

2.3 Isotope biochemistry
Isotopic composition in the biosphere is highly variable and is affected by a variety of different processes depending on the element in question (Hoefs, 2009: 93). Isotope fractionation is the term that describes these processes which cause the relative abundance of difference in isotopes between substances, or the partitioning of the heavier and lighter isotopes (Tiwari et al., 2015).

The ratios of $^{13}C/^{12}C$, $^{15}N/^{14}N$, $^{18}O/^{16}O$, $^{87}Sr/^{86}Sr$ in the environment and the food chain are therefore changeable and depend on many different variables. These natural variations in isotope ratios in the ecosystem form the basis of IA in archaeology and ecology, as measurable differences can be associated with human/animal behaviours. Below some of these environmental variables such as photosynthesis, water availability, temperature, altitude and geology will be discussed.

Bone is generally the most common tissue analysed in archaeological IA, however dental tissues are also often studied. The substances analysed here are not all strictly "biomolecules" as some are inorganic substances (i.e. enamel carbonate), however bioapatite is synthesised as part of a biological system during life, so they are broadly grouped here under biochemistry.
2.3.1 Isotope variation in nature

Differences in the environment will impact on the stable isotope values of certain elements which are “bioavailable” or able to be ingested and incorporated into biological beings. Physiological factors also alter the stable isotope ratios of biological tissues by impacting tissue formation and isotope fractionation and partitioning. These isotopic variations can be caused by macro- and micro-scale changes in the environment and are detectable at a variety of scales. Different kinds of ecosystems and environmental systems will result in variations in stable isotopes of the water, plants and animals in those conditions; and in archaeology and ecology these differences are central to our research.

As archaeologists we can be interested in one or all of these factors influencing stable isotope values in tissues and disentangling them can be difficult. Some of the main physiological factors which can alter isotopic values were mentioned above – nutritional stress, other health events, sex and age. These physiological factors and diet add to the fractionation and variation we observe.

The sub-sections below will go through element-by-element factors causing variation in both producers and consumers which are relevant to this research.

2.3.1.1 Carbon

Carbon has two stable isotopes $^{12}\text{C}$ (98.93% of the natural abundance) and $^{13}\text{C}$ (1.07%) and their relative abundances can change due to a variety of natural fractionation processes (Hoefs, 2009: 48). I will first consider carbon producers and terrestrial ecosystems. Plants are the base of most terrestrial food chains and the isotopic variation in these organisms will be passed onto consumers (Farquhar et al., 1989; O’Leary, 1988; Tieszen et al., 1983). Carbon in plant tissues is a product of photosynthesis where atmospheric CO$_2$ is converted into oxygen (expelled) and glucose, and fractionation occurs during this process (Farquhar et al., 1989; O’Leary, 1988). There are three photosynthetic pathways – C$_3$, C$_4$ and CAM – each fixes carbon in a different way which results in $\delta^{13}\text{C}$ value differences between plant types (Farquhar et al., 1989; Hoefs, 2009: 52; O’Leary, 1988).
As this study focuses on Early Medieval Europe, and predominantly on Britain, only C$_3$ and C$_4$ plants are of interest here (CAM plants being desert species such as cacti and succulents). Millet, sago and amaranth are the only known C$_4$ plants to be consumed in Continental Europe in the Early Middle Ages, but were not known in Britain until the later Middle Ages (Alt et al., 2014; Ganzarolli et al., 2018; Hagen, 2006: 23, 33, 38–39; Hakenbeck et al., 2017). C$_3$ plants have a possible $\delta^{13}$C range of between -38 to -22‰, and C$_4$ plants between -9 and -21‰, when analysed in bulk with some variation between species and plant tissues (Hoefs, 2009: 52; O’Leary, 1988; Tieszen, 1991; van der Merwe, 1982). Photosynthesis and thus stable isotope ratios in plants (of both carbon and nitrogen) are inextricably linked with the plant’s growing environment – water availability, light, altitude, heat, the canopy effect, salinity and plant physiology can all impact on plant stable isotopes (Farquhar et al., 1989; Lightfoot et al., 2016, 2020; O’Leary, 1988; Tieszen, 1991; van der Merwe, 1982).

Isotopic ratios of consumers vary, and it has been shown that, due to a combination of physiology and diet, different species have markedly different $\delta^{13}$C values of different tissues. This allows us to distinguish herbivores, omnivores and carnivores and aid in trophic level estimations (Hedges, 2003; Jim et al., 2004; Lee-Thorp et al., 1989; Passey et al., 2005; Zhu and Sealy, 2019).

Carbon in freshwater and marine ecosystems is complex as it is derived from a variety of sources all with varied isotopic values. Aquatic plant diversity and the extended food webs in aquatic environments mean that, especially in freshwater environments, isotopic signatures of organisms are highly variable with large inter- and intra-species variations in fish being reported (Ervynck et al., 2018; Guiry, 2019; Hedges and Reynard, 2007; Hoefs, 2009: 153). Freshwater fish species overlap terrestrial and marine species in both $\delta^{13}$C and $\delta^{15}$N values for bone collagen, highlighting this complexity (Jones and Waldron, 2003; Nehlich et al., 2010). Sulphur isotopes show great promise in helping to isotopically tease apart freshwater species and hopefully this avenue of research will expand (Nehlich, 2015; Nehlich et al., 2010, 2011; Privat et al., 2007).
Marine ecosystems, whilst complex in terms of food chains and the carbon reservoir effect, are isotopically distinct from terrestrial ecosystems due to this complexity and length of food chains. Marine $\delta^{13}C$ values are higher compared to terrestrial environments and are thus easily distinguished isotopically in the tissues of producers and consumers (Chisholm et al., 1982; Müldner, 2016; Schoeninger and DeNiro, 1984; Tauber, 1981). However, there is a confounding factor of overlap between $\delta^{13}C$ values of $C_4$ consumers or mixed $C_3/C_4$ consumers (see above) and marine consumers, due to the complexities inherent in these plants and ecosystems and isotopic mixing (Chisholm et al., 1982; Lewis and Sealy, 2018; van der Merwe, 1982). Therefore, it is often difficult to separate these consumption patterns isotopically without good baseline evidence or other contextual (archaeological or historical) information to constrain interpretations.

2.3.1.2 Nitrogen

Nitrogen also has two stable isotopes, $^{14}N$ and $^{15}N$, representing 99.63% and 0.37% of the natural abundance, respectively (Hoefs, 2009: 54). In animal tissues $\delta^{15}N$ increases stepwise up the food chain so that carnivores have higher values than omnivores and omnivores higher than herbivores (Ambrose, 1986, 1991; Hedges, 2003; Hedges and Reynard, 2007). Many of the causes of $\delta^{15}N$ variation in nature are the same as $\delta^{13}C$ described above – water availability, heat, the canopy effect etc. Differences in ecosystems are as apparent in $\delta^{15}N$ values as they are in $\delta^{13}C$, aiding in the distinction between terrestrial and marine resource consumption.

In terrestrial environments, plants assimilate nitrogen from the atmosphere and decaying organic matter through two pathways – direct $N_2$ fixation from the atmosphere, and assimilation with the assistance of soil microbes or microbes living in a commensal relationship with the plant’s roots (e.g. legumes and clover) (Hoefs, 2009: 54–55). These pathways result in different but minimal fractionation in nitrogen values – direct $N_2$ fixers have $\delta^{15}N$ values which are very close to atmospheric values (0‰) (Hoefs, 2009: 54–55; Robinson, 2001). Most terrestrial plants are non-fixers so assimilate their nitrogen from the soil, and, as soil nitrogen values are extremely variable and can be altered by manuring and other processes,
plants can have $\delta^{15}N$ values between 2 and 10‰ (Bogaard et al., 2007; Hoefs, 2009: 55; Lightfoot et al., 2016, 2020; Schoeninger and DeNiro, 1984).

Nitrogen in marine ecosystems derives from both fixation by algae and phytoplankton, and also from decomposing organic matter (Gruber, 2004, 2008). Evaporation is the main cause of de-nitrification in oceans and favours the evaporation of the lighter isotope thus leaving marine systems isotopically enriched in $^{15}N$. Combined with the longer marine food chains (compared to terrestrial), marine organisms tend to have enriched $\delta^{15}N$ values (Richards and Hedges, 1999; Schoeninger and DeNiro, 1984).

Similarly, the length of food chains and variability of sources are the main driving factors behind freshwater nitrogen isotopic variation, as described above for carbon. They overlap considerably with both terrestrial and marine values (just as for carbon) and more work with sulphur and experimental studies are needed to further elucidate the complexities of nitrogen in freshwater ecosystems (Guiry, 2019; Hoefs, 2009: 154; Jones and Waldron, 2003; Privat et al., 2007).

2.3.1.3 Oxygen

An extensive review of archaeological applications of IA using oxygen and the underlying principles has been recently published by Pederzani and Britton (2019). Variation in $\delta^{18}O$ baselines is due to the hydrological cycle where water is continuously rained out and evaporated. During this cycle, proximity to coast (continentality), seasonality, temperature, altitude, amount of rainfall and humidity all play a role in $\delta^{18}O$ variability (Bowen and Revenaugh, 2003; Lightfoot and O'Connell, 2016; Pederzani and Britton, 2019; Rozanski et al., 1992, 2013). Thus $\delta^{18}O$ values vary in relatively predictable patterns geospatially and climatically (see Figure 2-1).
δ¹⁸O fractionation is largely driven in natural systems by evaporation, whereby (as above with carbon and nitrogen) the preferential evaporation of the lighter isotope to the heavier leaves bodies of water which are either large or in hot climates enriched in $^{18}$O (Bowen and Revenaugh, 2003; Iacumin et al., 1996; Longinelli, 1984; Pederzani and Britton, 2019; Rozanski et al., 1992, 2013).

2.3.1.4 Strontium

Strontium has four stable nuclides/isotopes – $^{84}$Sr, $^{86}$Sr, $^{87}$Sr and $^{88}$Sr, with $^{87}$Sr being the radiogenic daughter of radioactive $^{87}$Rb (Bataille et al., 2020; Krabbenhöft et al., 2009; Schaefer, 2016; Willmes et al., 2018). Therefore $^{87}$Sr has a variable abundance in geological formations which roughly equates to the age of the rock, and the $^{87/86}$Sr of geologies are both mineral dependent and time-dependent which aids in provenancing giving an indication of both the age and mineral composition (Bataille et al., 2020; Brown and Brown, 2011: 80, 85–87; Evans et al., 2012; Price and Burton, 2012: 94–95).

Bioavailable strontium enters the food chain through plants and water which ultimately derive their $^{87/86}$Sr values from the weathering of the underlying geology.

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that they have grown in or pass through (Evans et al., 2010, 2012). Bioavailable strontium can also be affected by atmospheric events such as sea spray, rainfall and flooding, or dust which introduce strontium from non-local sources. Anthropogenic influences from agriculture (e.g. fertilizers), pollution and food processing (e.g. through use of mill stones) are now becoming better understood (Evans et al., 2010; Maurer et al., 2012; Thomsen and Andreasen, 2019; Willmes et al., 2018).

2.3.2 Cooking, brewing and stewing
Aside from the natural variation in stable isotopes, cooking and other food producing processes are also likely to change the stable isotope values of the things being consumed. Cooking, brewing and stewing are unique to humans and should be considered when using IA to investigate past human behaviours. This is a brief overview of the isotopic impact of these processes on food and drink and will be considered together with what is known of Early Medieval diets and foodways in later chapters.

The heating processes involved in making drinks such as teas or worts, alcoholic distillation or stewing cause liquid evaporation which leaves the product enriched in the heavier isotope (Brettell, Montgomery, et al., 2012; Pederzani and Britton, 2019). Mammalian milk has also been shown to be enriched compared to body water and drinking water values (Lin et al., 2003; Pederzani and Britton, 2019). As shown in Figure 2-2, fractionation of oxygen isotopes from source water varies considerably depending on the type of heating and preparation process (or, in the case of milk, the natural formulation of it by mammary tissues), and this in turn affects the $^{18}$O values of consumers. Brettell et al. (2012) estimated that $\delta^{18}$O values may be enriched by as much as $+2.3\%$ or possibly more, given the historical and archaeological evidence. In conjunction with $\delta^{15}$N values this can provide insights for weaning studies or evidence of dairying.

One high profile example of the “brewing and stewing” principle is King Richard III; significant differences between the $\delta^{18}$O values of his various bones and teeth suggest an increased consumption of wine later in life, in line with historical
sources and estimates of the effect of consuming wine in large quantities instead of water (Brettell, Montgomery, et al., 2012; Lamb et al., 2014).

It is largely oxygen we have to worry about in this regard, but more experimental work is revealing that various cooking processes also cause perceptible fractionation with meat $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ values, and charring also impacts on plant tissues. Our “baselines” from animal bone (discussed below) may not be entirely accurate for what is actually being consumed as bone itself is not usually eaten by humans (Royer et al., 2017). But there is more work to be done quantifying these processes and to better incorporate this information into mixing models to account for changes in food isotope ratios and their incorporation into consumer tissues.

Humans are unique in their consumption of artificially altered beverages and foods in high abundances. The “brewing and stewing” effect is a confounding factor in some archaeological stable isotope studies using oxygen and is difficult to correct for. That being said, if an individual’s $\delta^{18}O$ values vary dramatically from the expected values, and migration can be ruled out for other reasons, it may indicate consumption of these kinds of liquids rather than enriched $^{18}O$ in water by natural means. In essence, enriched $^{18}O$ values can point to foodways which involve a significant amount of brewing and stewing as shown with King Richard III (Brettell, Montgomery, et al., 2012; Lamb et al., 2014; Pederzani and Britton, 2019).
2.3.3 Baselines

The creation of baselines is extremely important in stable isotope ecology. For diet studies they allow for the calculation of the trophic position of the consumer, and in mobility studies they give an environmental base map with which to compare values for goodness of fit to aid in provenancing. In dietary studies they can change interpretations considerably as underlying variability in the food web will be passed up to consumers, and differences between groups may not be due to dietary choices of the consumer but down to primary producers, foddering practices or other variation in the plant and animal populations (Bownes et al., 2018; Casey and Post, 2011; Schulting et al., 2017). Similarly, in mobility studies a good understanding of past climate, water sources and underlying geology is necessary to construct baselines but also to interpret results from human and animal tissues.

For oxygen and strontium work, given the above factors influencing variability, baselines are relatively straightforward to construct. Strontium isotope maps are drawn from geological sampling of soils and bedrock, and are getting increasingly accurate, particularly in the UK and the rest of Europe. Where strontium isotopic base maps are not available, maps of underlying geology are a good alternative as given the principles described above, the age and formation processes of the rock
can be determined and $^{87/86}$Sr values estimated. However, there can be large differences between geological strontium and bioavailable strontium values. Strontium studies of archaeological fauna which are assumed to be local can be used, and modern soils, water and vegetation are also good indicators of bioavailable strontium (Bataille et al., 2018; Evans et al., 2010; Maurer et al., 2012; Thomsen and Andreasen, 2019; Willmes et al., 2018). Recently the bioavailable strontium values of Britain's geology have been made accessible through the British Geological Survey as an online interactive map alongside oxygen and sulphur values, but more work on base maps is needed outside of the UK especially when considering long distance migration (Brettell, Evans, et al., 2012; British Geological Survey, n.d.; Evans et al., 2010, 2012; J Evans et al., 2018; Evans and Tatham, 2004).

Oxygen baselines can similarly be obtained from water sampling or by using faunal carbonate/phosphate values. There are several oxygen isotope base maps available for the UK and Europe, with online modelling tools also available to predict $\delta^{18}O$ values for precipitation given latitude, longitude and altitude of a given site (GJ Bowen, 2019; Bowen and Revenaugh, 2003; British Geological Survey, n.d.; J Evans et al., 2018; Lightfoot and O’Connell, 2016; Pederzani and Britton, 2019). Ideally water and faunal samples from as close to the presumed occupation site or cemetery as possible would be obtained and integrated with precipitation models to construct a ‘local’ baseline which is also statistically constrained with suitable error ranges attached to help aid paleoenvironmental and migration analyses (Lightfoot and O’Connell, 2016; Pederzani and Britton, 2019).

Commonly in archaeological IA human values are compared to faunal ones (usually herbivores) to calculate trophic position; however, this requires a thorough understanding of the available foodstuffs for the consumer in question, and the natural variation in $\delta^{13}C$ and $\delta^{15}N$ values outlined above. If all of the sources of variation in and between consumers and producers at all levels are not accounted for, there can be serious problems in estimating trophic levels and the cultural and biological implications drawn from IA data. For studies using $\delta^{13}C$ and $\delta^{15}N$ values there are two main ways to construct baselines:
1. By directly measuring the $\delta^{13}$C and $\delta^{15}$N values of plant resources as primary producers or
2. By measuring $\delta^{13}$C and $\delta^{15}$N of herbivorous proxy species e.g. cattle or ovicaprids (as used here)

These averaged values are then subtracted from human values either on an individual or site-specific basis (assuming the humans in a burial population lived and ate locally for the baseline to be appropriate). Due to the scarcity of archaeological plant remains, especially for the Early Medieval period (see Chapter 1), the use of proxy species is very common, however this can be problematic, as outlined above. This approach is very broad-brush strike and is heavily reliant on the preservation and identification of faunal remains from nearby sites, which is not always possible. Despite the difficulties, baselines are extremely important especially in comparative studies as there are often significant underlying environmental differences between sites that may not be apparent from human values alone (Bownes et al., 2018; Casey and Post, 2011; Hull, 2007; Mallet, 2016).

2.3.4 Collagen structure, production, and turnover in bone and dentine

Collagen is a structural protein found in many animal bodily tissues, with 28 known types (Smith and Rennie, 2007). Aside from a few exceptions, in archaeological contexts collagen survives only in skeletal and dental tissues. I will therefore focus on Type I collagen found in bone (and the most abundant in the body). The organic component of mammalian bone is primarily made of Type I collagen, and this is what gives living bone its elasticity, with mineral bioapatite embedded in the collagen fibres, giving the structural strength (and some protection against diagenesis). Collagen is secreted by osteoblasts during bone formation and remodelling. Type I collagen has a triple helical structure of three polypeptides in a tropocollagen molecule. These are organised as fibrils forming fibres which are embedded with the bone bioapatite mineral (Brown and Brown, 2011: 92–94; Chenery et al., 2012; DeNiro, 1985; Smith and Rennie, 2007). The collagen fibrils can form different bone microstructures – woven, lamellar and parallel-fibred bone but two macrostructures are visible under light microscopy – compact/cortical bone and cancellous/trabecular or “spongy” bone (Brown and Brown, 2011: 92–94). Due to the arrangement of osteoblasts and blood supply to different types of
bone, as well as the size and density of different bones and the mechanical stress they are under, the remodelling rates differ markedly.

Collagen in bone and dentine is composed of both essential and non-essential amino acids, and thus reflects diet but also other metabolic processes and nutrient pools in the body. The nitrogen in collagen derives primarily from dietary protein but is affected by the nitrogen balance of an individual and therefore by nutritional stress, whereas carbon can be derived from dietary protein as well as carbohydrates and fats which can be from the consumer's own body (France and Owsley, 2015; Fuller et al., 2005; Hedges, 2003; Lee-Thorp et al., 1989; Makarewicz and Sealy, 2015; O'Connell et al., 2012). The complex interplay of different metabolic pathways is still poorly understood, and dietary routing in isotope ecology, especially in humans, still has a lot of avenues to explore. More work is needed to verify the rate of bone turnover and isotopic fractionation experimentally (Hedges et al., 2007; Hobson and Clark, 1992; Parfitt, 2002; Shin et al., 2004; Tieszen et al., 1983). Due to differences in structure between trabecular and compact bone it is assumed that trabecular bone (e.g. majority of rib bone) has a much faster turnover rate and thus represents a shorter window for diet, while long bones largely made of compact bone have far longer turnover periods; however exact rates are still elusive (Hedges et al., 2007; Sealy et al., 1995; Smith and Rennie, 2007).

Similarly dentine is primarily composed of bioapatite with approximately 20% of the structure being Type I collagen, which is synthesised by odontoblasts in a variety of tubule structures (Brown and Brown, 2011: 100; Goldberg et al., 2011). Unlike bone, dentine usually does not remodel once formed, so turnover rates are not a concern in the same way, however, dietary routing and changes to metabolism (e.g. stress events) are.

Nitrogen balance is the equilibrium in the body between protein intake (from diet) and loss (through metabolism and excretion). If the body is not in a state of equilibrium, then it may start to self-metabolise (break down its own tissues for fuel). The balance between energy intake and expenditure can be disturbed during
periods of nutritional stress or illness. Studies suggest that other events may also impact on isotope values of otherwise healthy individuals such as lactation, (normal) pregnancy and growth in puberty where the needs of the body exceed the dietary input, similar to periods of illness (Clark et al., 2016; Fuller et al., 2005; Haydock et al., 2013; Nitsch et al., 2010; Reitsema, 2013).

In humans there has been work done on $\delta^{15}N$ values and nutritional stress events which show how important nitrogen balance is, and how self-metabolism kicks in during starvation. Fuller et al. (2005) demonstrated this effect in the hair of pregnant women experiencing severe morning sickness, showcasing how nutritional stress impacts $\delta^{15}N$ values (they increase) but not $\delta^{13}C$ values. Their tag line “why you’re not what you eat during nutritional stress” highlights the complexity of dietary routing and metabolism and its implications for ecological IA applications (Fuller et al., 2005, 2006). The $\delta^{15}N$ stress effect is exemplified further by work on Irish famine populations where a “stress bubble” is apparent in the incremental dentine of those who survived the famine (Beaumont and Montgomery, 2016). Nutritional stress of both mothers and babies is therefore apparent in both their tissue stable isotope values, making early life health events “trackable” using IA (Beaumont et al., 2015, 2018; Crowder et al., 2019; Fuller et al., 2005, 2006; Haydock et al., 2013).

Where diets are insufficient in protein (either through famine or by choice e.g. veganism) carbon will be routed from the whole diet into collagen, so whilst no “stress bubble” is seen, $\delta^{15}N$ values will be low, and the sources of carbon differ, affecting interpretation of stable isotope values. As protein increases in the diet the amount of carbon sourced from protein will also increase (Codron et al., 2012, 2018; Jim et al., 2004, 2006). There is still debate over where and in what proportions the non-protein component of carbon in collagen comes from – carbohydrates, lipids, or both, and how much of this is dietary or self-metabolised.

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5 A “stress bubble” on an incremental dentine chart occurs when the $\delta^{15}N$ values go up and the $\delta^{13}C$ values more or less remain constant around the nutritional stress event thus creating co-occurring anomalies and a “bubble” on the chart is formed.

6 Isotopic analysis of incremental dentine, a technique not used here, uses fine slices along a cross-section of the tooth root to look at diet through the period of that tissue’s formation (Beaumont et al., 2015, 2015, 2018; J. Beaumont et al., 2013; Beaumont and Montgomery, 2016; Craig-Atkins et al., 2018; King et al., 2017).
like with nitrogen (Ambrose and Norr, 1993; Codron et al., 2018; Froehle et al., 2010; Hedges, 2003; Jim et al., 2004, 2006; Lee-Thorp et al., 1989; Tieszen et al., 1983).

Veganism in current human populations is an example of the effect low-protein diets can have on carbon and nitrogen stable isotope values in human tissues, making them appear similar to faunal herbivores. Controlled studies show marked differences, particularly in the δ^{15}N values of individuals with negligible to no animal protein in their diet compared to individuals with varying levels of omnivory (Katzenberg and Krouse, 1989; Minagawa, 1992; O’Connell et al., 2012; O’Connell and Hedges, 1999; Petzke et al., 2005). Further to the differences caused by selective diets of humans, studies comparing tissue spacing of δ^{13}C between collagen and apatite (see below for more detail on apatite) have shown that there are trophic and species-specific models for carbon dietary routing, some of which may be driven by diet, some by physiology, and likely a combination of both. What is clear is that there are very obvious differences between species occupying specific dietary niches (Codron et al., 2018; Göhring et al., 2019; Hedges, 2003; Lee-Thorp et al., 1989; Loftus and Sealy, 2012; Zhu and Sealy, 2019).

In humans and other animals there is also the suggestion that other physiological distinctions such as age and sex (beyond weaning age) may affect isotopic fractionation due to metabolic differences. There is no experimental evidence as yet for differences in male and female animals (excluding the pregnancy and nursing effects) in δ^{13}C and δ^{15}N values due to physiology. The physiological effects of age on isotopic composition are more difficult to determine due to the problems with tissue turnover rates mentioned above, but aside from weaning there may be other age related metabolic processes that cause not only changes in the skeleton on a macro scale but also biochemically; however more work needs to be done in this area (Beaumont et al., 2018; Minagawa and Wada, 1984). There is evidence in non-human animals that age stage is linked to diet, but as yet for humans this seems to be largely culturally mediated (Bădescu et al., 2017; Borrell et al., 2013; Katzenberg et al., 1993; MacKenzie et al., 2012; Waterman et al., 2016).
2.3.5 Bioapatite structure, formation, and dietary routing

As stated above, bioapatite is the mineral portion of biologically formed tissues. Bioapatite in bones and teeth is laid down by osteoblasts and odontoblasts respectively with some organic components interspersed in the mineral matrix. Enamel is different to bone and dentine as it is almost entirely mineral with less than 5% consisting of amelogenin. Enamel incorporates, like bone, other minerals in the carbonate structures such as calcium and strontium (Brown and Brown, 2011: 100–101; Goldberg et al., 2011). Bioapatite has a highly variable chemical stoichiometry but for simplicity in IA is often referred to as its phosphate or structural carbonate components (Driessens, 1980; Elliott, 2002; France and Owsley, 2015; Pederzani and Britton, 2019; Wopenka and Pasteris, 2005).

The $\delta^{18}O$ values of bioapatite are determined by the isotopic composition of body water in mammals, which is derived from consumed oxygen sources such as inhaled air, drinking water and oxygen components of food (structural oxygen and food water), in a mass balance with excretions (e.g. water vapour through breath or sweat, water in waste products and exhaled carbon dioxide) (Pederzani and Britton, 2019). This is pulled from the blood by osteoblasts/odontoblasts during tissue formation/remodelling. Both carbonate and phosphate groups in bioapatite form in equilibrium with body water with a relatively constant offset to one another, making conversion (see Chapters 3 and 4) possible. Metabolism plays a crucial role in this process and thus there are marked species-specific differences in the relationship between the $\delta^{18}O$ values of body water and drinking water (Bryant and Froelich, 1995; Göhring et al., 2019; Kohn, 1996; Kohn et al., 1996; Luz et al., 1984; Pederzani and Britton, 2019). As body water is largely derived from atmospheric water, it is not only representative of dietary water intake but also of the environment which that water came from (Pederzani and Britton, 2019; Price and Burton, 2012: 91–92; White et al., 1998). Environmental variation in $\delta^{18}O$ values, the driving factors of this variation and sources of cultural alteration of these stable isotope values are discussed in more depth above.

Dietary routing for carbon has been discussed for collagen above, and it is the relationship between diet and the carbon portion of enamel carbonate which
makes it attractive for use in archaeological IA investigations. Slightly different to
the routing of carbon in collagen, the carbon in bioapatite is derived from blood
bicarbonate, which in turn derives from respiration and therefore is thought to
represent whole diet, with species differences thought to be largely due to
physiology rather than differences in the magnitude of fractionation between the
mineral and body fluid (Ambrose and Norr, 1993; Hedges, 2003; Howland et al.,
2003; Passey et al., 2005; Tieszen and Fagre, 1993; Zhu and Sealy, 2019). Enamel
carbonate therefore 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 δ¹³C values of collagen.

Enamel, like dentine, does not remodel during life, unlike bone apatite. Therefore, it
represents a fixed point in early life (often an average over a few of years
depending on the tooth selected) for the incorporation of those elements into the
tissue matrix – whether they be carbon, oxygen or strontium. Hence it is a useful
tool for mobility and diet studies (Brown and Brown, 2011: 100–101; Chenery et
al., 2012; Evans et al., 2012; Pederzani and Britton, 2019; Price and Burton, 2012:
91–92, 95–98).

2.3.6 Tooth formation timings
As briefly mentioned above different bones in the human body are assumed to have
different formation and turnover rates, and similarly other tissues (i.e. dentine and
enamel) are likewise formed at different stages of development. Therefore, different
tissues and tissue combinations can be used to inform about diet and/or mobility at
different life stages and throughout the life course. As stated above teeth, both enamel
and dentine, represent in adults dietary input from earlier in life than bones due to their
formation timings and their lack of remodelling during life. However, tooth selection is
also crucial as different teeth form at different times, and there are differences in
formation timings as well as dietary routing for the enamel versus the dentine in each
tooth. Below in Table 2-1 the formation timings for primary (deciduous or milk)
dentition and secondary (permanent or adult) teeth are summarised. As mentioned in
Chapter 4 secondary molars or secondary molars were selected for analysis due to their
similarity in formation ages and because they represent post-weaning but pre-adult diet.
In the larger databases used for meta-analyses any teeth with isotopic data were included but their tooth type noted, the implications for inter-tooth comparisons will be briefly discussed in Chapter 5, however a large in-depth comparison and break down of tooth types was outside the scope of this thesis, although age implications were considered (see Chapter 7).

<table>
<thead>
<tr>
<th>Deciduous Dentition</th>
<th>Tooth</th>
<th>Hard Tissue Formation begins</th>
<th>Crown completed</th>
<th>Emergence</th>
<th>Root Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxillary teeth</td>
<td>Central incisor</td>
<td>4 mo in utero</td>
<td>4 mo</td>
<td>7.5 mo</td>
<td>1.5 yr</td>
</tr>
<tr>
<td></td>
<td>Lateral incisor</td>
<td>4.5 mo in utero</td>
<td>5 mo</td>
<td>9 mo</td>
<td>2 yr</td>
</tr>
<tr>
<td></td>
<td>Canine</td>
<td>5 mo in utero</td>
<td>9 mo</td>
<td>18 mo</td>
<td>3.25 yr</td>
</tr>
<tr>
<td></td>
<td>1st molar</td>
<td>5 mo in utero</td>
<td>6 mo</td>
<td>14 mo</td>
<td>2.5 yr</td>
</tr>
<tr>
<td></td>
<td>2nd molar</td>
<td>6 mo in utero</td>
<td>11 mo</td>
<td>24 mo</td>
<td>3 yr</td>
</tr>
<tr>
<td>Mandibular teeth</td>
<td>Central incisor</td>
<td>4.5 mo in utero</td>
<td>3.5 mo</td>
<td>6 mo</td>
<td>1.5 yr</td>
</tr>
<tr>
<td></td>
<td>Lateral incisor</td>
<td>4.5 mo in utero</td>
<td>4 mo</td>
<td>7 mo</td>
<td>1.5 yr</td>
</tr>
<tr>
<td></td>
<td>Canine</td>
<td>5 mo in utero</td>
<td>9 mo</td>
<td>16 mo</td>
<td>3 yr</td>
</tr>
<tr>
<td></td>
<td>1st molar</td>
<td>5 mo in utero</td>
<td>5.5 mo</td>
<td>12 mo</td>
<td>2.25 yr</td>
</tr>
<tr>
<td></td>
<td>2nd molar</td>
<td>6 mo in utero</td>
<td>10 mo</td>
<td>20 mo</td>
<td>3 yr</td>
</tr>
<tr>
<td>Permanent Dentition</td>
<td>Maxillary teeth</td>
<td>Central incisor</td>
<td>3-4 mo</td>
<td>4-5 yr</td>
<td>7-8 yr</td>
</tr>
<tr>
<td></td>
<td>Lateral incisor</td>
<td>10-12 mo</td>
<td>4-5 yr</td>
<td>8-9 yr</td>
<td>11 yr</td>
</tr>
<tr>
<td></td>
<td>Canine</td>
<td>4-5 mo</td>
<td>6-7 yr</td>
<td>11-12 yr</td>
<td>13-15 yr</td>
</tr>
<tr>
<td></td>
<td>1st premolar</td>
<td>1.5-1.75 yr</td>
<td>5-6 yr</td>
<td>10-11 yr</td>
<td>12-13 yr</td>
</tr>
<tr>
<td></td>
<td>2nd premolar</td>
<td>2-2.25 yr</td>
<td>6-7 yr</td>
<td>10-12 yr</td>
<td>12-14 yr</td>
</tr>
<tr>
<td></td>
<td>1st molar</td>
<td>Birth</td>
<td>2.5-3 yr</td>
<td>6-7 yr</td>
<td>9-10 yr</td>
</tr>
<tr>
<td></td>
<td>2nd molar</td>
<td>2.5-3 yr</td>
<td>7-8 yr</td>
<td>12-15 yr</td>
<td>14-16 yr</td>
</tr>
<tr>
<td></td>
<td>3rd molar</td>
<td>7-9 yr</td>
<td>12-16 yr</td>
<td>17-21 yr</td>
<td>18-25 yr</td>
</tr>
<tr>
<td>Mandibular teeth</td>
<td>Central incisor</td>
<td>3-4 mo</td>
<td>4-5 yr</td>
<td>6-7 yr</td>
<td>9 yr</td>
</tr>
<tr>
<td></td>
<td>Lateral incisor</td>
<td>3-4 mo</td>
<td>4-5 yr</td>
<td>7-8 yr</td>
<td>10 yr</td>
</tr>
<tr>
<td></td>
<td>Canine</td>
<td>4-5 mo</td>
<td>6-7 yr</td>
<td>9-10 yr</td>
<td>12-14 yr</td>
</tr>
<tr>
<td></td>
<td>1st premolar</td>
<td>1.75-2 yr</td>
<td>5-6 yr</td>
<td>10-12 yr</td>
<td>12-13 yr</td>
</tr>
<tr>
<td></td>
<td>2nd premolar</td>
<td>2.25-2.5 yr</td>
<td>6-7 yr</td>
<td>11-12 yr</td>
<td>13-14 yr</td>
</tr>
<tr>
<td></td>
<td>1st molar</td>
<td>Birth</td>
<td>2.5-3 yr</td>
<td>6-7 yr</td>
<td>9-10 yr</td>
</tr>
<tr>
<td></td>
<td>2nd molar</td>
<td>2.5-3 yr</td>
<td>7-8 yr</td>
<td>11-13 yr</td>
<td>14-15 yr</td>
</tr>
<tr>
<td></td>
<td>3rd molar</td>
<td>8-10 yr</td>
<td>12-16 yr</td>
<td>17-21 yr</td>
<td>18-25 yr</td>
</tr>
</tbody>
</table>

Table 2-1: Primary (deciduous) and secondary (permanent) tooth formation and emergence times (Scheid, 2007: 328).
2.3.7 Diagenesis

For archaeological scientists working with biological remains, diagenesis is of major concern. The processes of post-mortem decay are complex and highly dependent on funerary treatment (if any) and the burial environment. Histology and forensic experiments indicate that the inorganic portion of bone is being broken down as part of microbial decay, but collagen is often well-protected in the bone matrix and is a difficult protein to degrade (Brown and Brown, 2011: 94–101; Hedges, 2002; Nelson et al., 1986; Wang and Cerling, 1994). Water and acidic soils are also major culprits in the breakdown of skeletal remains and can speed up this process. Conversely certain burial environments aid in organic preservation and slow decay – such as anaerobic environments e.g. bogs. Skeletal and dental tissues are far more resistant to decay than soft tissues, and enamel as the hardest tissue is most resistant to diagenesis (Brown and Brown, 2011: 94–101; Hedges, 2002; Hollund et al., 2014, 2015; Nelson et al., 1986; Wang and Cerling, 1994). The literature on dental tissue diagenesis is sparser than that on bone, however experimental work does suggest that enamel undergoes far less ion exchange with the burial environment than bone or dentine apatite and collagen, and its crystallinity is highly resistant to diagenesis (Bell et al., 1991; Brown and Brown, 2011: 100–101; Dauphin and Williams, 2004; Hollund et al., 2014, 2015). Due to collagen’s fibre structure it is less chemically exchangeable with the burial environment than bone apatite (hence the choices of material for this study, see Chapter 4), but over time it does degrade and undergo diagenesis. Hence collagen quality assessment is extremely important for the reliability of stable isotope ratios and their use as dietary indicators (Ambrose, 1990; Brown and Brown, 2011: 94–101; DeNiro, 1985; Ubelaker et al., 1995; van Klinken, 1999). For details on quality assessment procedures, see Chapter 4.

2.4 Statistical modelling and ecology

Archaeological (S)IAs use frequentist statistics and report p-values overwhelmingly without much critical thought to the suitability of the test or underlying assumptions that must be made to use them. However, many practitioners of IA in archaeology are increasingly following trends in ecology and incorporating more nuanced and powerful statistical analyses and modelling into
their work. With advances in Bayesian methods we now have at our disposal, methods which can deal with complex datasets, smaller sample sizes and the large amount of uncertainty that are inherent in archaeological datasets. Bayesian methods allow us to fit probability models to our data, incorporate various sources of uncertainty and prior knowledge into models (Bownes et al., 2017; Bürkner, 2018; Fernandes et al., 2014; Hopkins and Ferguson, 2012; Kruschke, 2013, 2014; Kruschke and Liddell, 2018; Lavine, 2019). They are more flexible and often more intuitive than frequentist alternatives and hence highly adaptable to multivariate datasets. Some of the Bayesian mixing models use a multi-level or hierarchical structure; however, for some isotope pairs (e.g. carbon and nitrogen) or for offsets and other relationships, researchers have been utilising multi-level linear models. This structure is so useful in ecological and archaeological research because it can help account for intra-population variability, and explain individual level variation (for instance repeat measurements or several tissues from the same person having different values) and for other sources of variability at a variety of scales (Boecklen et al., 2011; Bürkner, 2017, 2018; Codron et al., 2018; Hopkins and Ferguson, 2012). For these reasons the approach taken in this thesis uses hierarchical structures in clustering and modelling (for more details see Chapters 3, 5-8).

2.5 Matching archaeological research problems and isotopic “answers”

Often the archaeological problems IAs can address are far narrower than the larger scale themes archaeologists want to investigate with these techniques (Price and Burton, 2012: 25–40). It is therefore extremely important to be clear about the abilities and limitations of IA of biological samples in an archaeological context. With the fundamentals of the technique outlined above and this thesis’ research objectives in mind, the kinds of questions the IA of each element (C, N, O and Sr) in archaeological remains can tackle are summarised below.

Some general research topics which are not specific to one element or require a combination of isotopes and/or tissues are:

- Collagen preservation to aid in radiocarbon determination or proteomic analyses/fingerprinting and assessing other aspects of diagenesis at a site
- Change of resource exploitation over time
• Dietary change over lifetime of an individual
• Mobility change over lifetime
• Marine vs. terrestrial resource exploitation
• Ruling out places of origin (combination of isotopes preferably)
• Stable isotope variability of a population (and the implications thereof)
• Seasonality (incremental sampling of dentine)
• Life histories – weaning, breastfeeding/lactation, nutritional stress/starvation e.g. famine

2.5.1 Carbon
Carbon stable isotope values can help to answer questions that are largely dietary in nature, and by extension also related to environment. Depending on whether values are from bioapatite or organic parts of tissues, or perhaps a comparison of the two, the questions vary. Using the principles outlined above on tissue formation, environmental variability and trophic levels, $\delta^{13}$C values can help differentiate trophic levels and resource exploitation. For example, consumption of C$_3$ versus C$_4$ plants and the consumption of marine versus terrestrial foods (in combination with nitrogen).

Since the $\delta^{13}$C values of tooth enamel carbonate reflect carbon isotopic ratios from the whole diet (including lipids and carbohydrates) rather than solely the protein portion of diet which collagen predominantly reflects, these can be integrated in analyses to consider those other dietary inputs often not accessible in collagen studies. In summary carbon IIA can help address:

• Consumption of C$_3$ versus C$_4$ plants
• Marine versus terrestrial resource exploitation (in conjunction with nitrogen)
• Whole diet versus protein sources and dietary routing

2.5.2 Nitrogen
Nitrogen stable isotopes in biological tissues are an extremely useful marker for dietary input but also nutritional stress events when studied in proteinaceous
tissues. They are used to estimate trophic level and marine resource consumption as well as dietary “stress”. The kinds of issues nitrogen can be used to investigate are:

- Trophic level estimation and relative amounts of animal protein consumption
- Marine versus terrestrial resource consumption in conjunction with carbon
- Weaning and breastfeeding
- Nutritional stress and self-metabolism

2.5.3 Oxygen

Oxygen in bioapatite, usually enamel, can help answer questions about the palaeoenvironment and, by extension environmental provenancing. Due to the ways in which oxygen isotopes vary based on climate they are good indicators of climatic zoning and fluctuation. Topics which can be informed by oxygen stable isotope ratios are:

- Provenancing or grouping of individuals based on the environmental factors mentioned above
- Palaeoenvironmental reconstruction
- Brewing and stewing – consumption of large amounts of fractionated liquids

2.5.4 Strontium

Strontium is perhaps the most straight forward of isotopes in terms of the questions it can answer as it is extremely hard, aside from diagenesis, for these ratios to be altered culturally, and should closely reflect bedrock geology from which food was sourced. Therefore, strontium values can aid in:

- Provenancing by geology – the age and mineral type of the geology

To be clear, isotopic analyses cannot on their own give a precise location for childhood origin, only rule out or narrow down possibilities; it cannot differentiate with absolute certainty between “vegetarian” and “omnivore” human diets, nor can
it give (even with stable isotope mixing models - SIMMs) exact percentages of different food stuffs in an individual's diet.

2.6 Summary

As discussed above, the use of IA in archaeology comes with some caveats and must be contextualised within the archaeological setting. That being said, IAs can still give us a wealth of information about the past. Scholars have called for an expansion of the use of IA in archaeology beyond questions of “reconstruction” by better integrating datasets (both isotopic and archaeological) (Bogaard and Outram, 2013; Makarewicz and Sealy, 2015; Reitsema, 2013). This study proceeds in that vein.

Whenever we move beyond a single point in IA (whether that point is in one, two or even three dimensions e.g. carbon, nitrogen and sulphur measurements on the same aliquot of collagen) comparisons are made, and even with that singular point there are correlations being drawn between ratios of different elements. All isotopic data is only meaningful in comparison, and singular absolute values are meaningless without context (either isotopic or archaeological). The most common comparisons are between different tissues in the same individual but also for the same element(s), and between different individuals. It is therefore vitally important to remember the principles discussed above in this chapter and consider what exactly we are comparing biochemically, as this impacts on our interpretations.

Some of the major confounding factors when it comes to stable isotope comparisons are offsets (of all kinds – baselines, tissue etc.), fractionation, and tissue formation and turnover (metabolism). These are complex biochemical processes which are poorly understood in many species, and in humans especially, and there is still much experimental work to be done. As such we have to be cautious when interpreting results of isotopic comparisons. There are many factors, both environmental and physiological, which impact on isotopic values in biological tissues. IA in archaeology can use the underlying principles of isotopic
variation to unpick past environmental variation and human behaviours when employed critically.

What this chapter has demonstrated are the principles and applications of (S)IA in (paleo)ecology more generally, highlighting confounding factors and the complex interplay between different biochemical processes which produce the values we interpret. Thoughtful interpretation, better scientific and statistical thinking is advised and carried into later chapters. In essence practice isotopic mindfulness.
3 Study Design for Meta-Analyses

This chapter details the collation of the databases holding the primary and legacy stable isotope, contextual site and associated bio-cultural data for the burials analysed. It describes the decisions made in the process of data collection and standardisation of variables. It also details the statistical methods and reproducibility principles utilised.

Computational meta-analyses are highly complex and an emerging style of research in archaeology (compared to psychology or clinical research); they are “neither quick nor easy” due to the challenges of data standardisation, cross-study comparisons and the statistical difficulties this poses (Berman and Parker, 2002; Greco et al., 2013; Kruschke and Liddell, 2018; van Wely, 2014). There are as yet no established analytical protocols to follow in our field, therefore this chapter details my study design.

3.1 Database collation

The skeletal remains, which were analysed isotopically for this thesis, needed to be contextualised by broader environmental, chronological, geographical and cultural data. To enable contextualisation and meta-analyses, previous stable isotope work on Early Medieval material and information on funerary practices, demography, dates of the graves, nearby settlements, type of environment and fauna also needed to be collected. Several databases were combined and developed to collect and house these data.

3.1.1 Spreadsheets and databases

There are two databases (MS Excel files) which form the foundation of the analyses here. They are a combination of my own primary stable isotope work detailed in the next chapter and legacy data. The two database files, and subsequent sheets therein, are separated due to the differing contextual data needs of biological tissues (e.g. species and animal groupings for fauna and not humans, extra information about teeth selection and whether they are bulk or incremental samples), the many conversions undertaken for bioapatite values (see below) and
for ease of import and analysis in R. The first database is dedicated to collagen carbon and nitrogen stable isotope values with separate spreadsheets for human bone, human dentine and faunal collagen (both bone and dentine) as per their varying biological metadata needs (see Figure 3-1 for details of headings). The other database is dedicated to human bioapatite (bone and enamel, although bone apatite was excluded for analysis here due to concerns over diagenesis, see Chapter 2) and as such contains δ$^{13}$C from structural carbonate alongside δ$^{18}$O values from both carbonate and phosphate analyses (and various oxygen conversions see section 3.1.6) and $^{87/86}$Sr values. Site and data information was collected in the same format for all databases and spreadsheets, with sample specific details varying for humans and fauna, and human tissue types. Further date categorisation was not undertaken for fauna as this was outside the scope of this thesis. Burial context data was not collected in the bioapatite database as that was not initially a key focus of this research, however it is hoped future work will pursue links between bioapatite isotope values and burial rites in more depth. Links between burial practice and mobility are however explored for Kent and East Sussex in Chapter 8. Further details about data standardisation and choices made are explained below.

Several databases from my own work and others were the foundation of my two core spreadsheets. These include two databases from my previous research, the “Anglo-Saxon” portion of Sarah Mallet’s DPhil database which she kindly gave me in 2016, and the database from the supplementary material of Lightfoot and O’Connell (2016) (Gosden, 2016; Leggett, 2014, 2016; Mallet, 2016). The headings used in each are summarised in Table 3-1 below. They were all combined, expanded upon and altered to suit the aims of my research, namely additional funerary archaeology data from burials, and environmental information from sites. For the bioapatite spreadsheet, the same general form of Lightfoot and O’Connell’s (2016) study was preserved, and all Early Medieval data from that study used. It was expanded by incorporating more recent studies, strontium values and additional contextual information. Their approach to the literature search and using the OIPC (Online Isotopes in Precipitation Calculator) to calculate Modelled Annual Precipitation (MAP) δ$^{18}$O values was also adopted (GJ Bowen, 2019; Bowen
and Revenaugh, 2003; Lightfoot and O’Connell, 2016). I searched the available literature for additional data published since 2016, with a cut off-date for inclusion of December 2019. Original citations for stable isotope data are given in my “reference” columns in both databases. Individual entries were assigned unique identification numbers – OSR denotes an entry in the bioapatite database, CNB for human bone collagen entries, CND entries from the dentine sheet and CNF faunal collagen from all skeletal elements (bone and dentine). The total number of entries for each spreadsheet are summarised Table 3-5.
Figure 3-1: Snapshot of spreadsheet headings and entries. Top-bottom: human bone carbon and nitrogen, human dentine carbon and nitrogen, human tooth enamel ($O$, $C$ and $Sr$), and fauna carbon and nitrogen.

<table>
<thead>
<tr>
<th>Author</th>
<th>Date</th>
<th>Headings Used in Databases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leggett</td>
<td>2014</td>
<td>Grave number, Furnished (Y/N), Body Position, Burial Orientation (N/SE/W), Burial Alignment (degrees), Burial Type, Age, Sex, Weapons, Jewellery/Ornamentation, Toilet Set/Personal Grooming, Chatelaine, Workbox, Textile Equipment, Straps and Buckles, Vessels, Padlock and/or Keys, Tools, Amulets, Coins, Knife, Other, Date</td>
</tr>
<tr>
<td>Leggett</td>
<td>2016</td>
<td>Type of Site, Source, Date, Diocese, Kingdom, Site Name, Site Size (Approx. Ha), Lat, Long</td>
</tr>
<tr>
<td>Lightfoot and O'Connell</td>
<td>2016</td>
<td>Site, Site Code, Site-combine (nearby sites combined), Country, Continent, Latitude, Longitude, Grid Square (European Sites Only), Alt (masl), Modelled Mean Annual Precipitation (MAP) (%), Date, Specimen Information, Element Sampled, Bone/Tooth, Tooth Grading, Carbonate $\delta^{18}O$ PDB (%), Carbonate $\delta^{18}O$ SMOW (%), Phosphate $\delta^{18}O$ SMOW (%), Reference</td>
</tr>
<tr>
<td>Mallet</td>
<td>2016</td>
<td>Reference, Date of Study, Archaeological Period, Date of Sample, Sub Period, Site, Region, Species, $\delta^{13}C$, $\delta^{15}N$, Sex, Age, Coastal_Inland, Latitude (North or South), Element Sampled, Laboratory</td>
</tr>
</tbody>
</table>

Table 3-1: Summary of databases used to construct the spreadsheets for this thesis.
3.1.2 Geographical regions and location data

For all sites, modern country and counties (or other administrative areas) were included for ease of recording, and finding collections and records pertaining to the sites. In the databases, countries were assigned numbers by approximate latitude north to south for data visualisation purposes. To better represent the contemporary geo-politics of Early Medieval Europe as well as climatic and geological zones I mapped sites to look for clusters and compared this with $\delta^{18}O$ and $^{87/86}Sr$ base maps (see Chapter 5), as well as cultural factors such as grave good styles and linguistics (Brownlee, 2019; Halsall, 1995, 2003). The result is Figure 3-2. These regions are not meant to imply static kingdoms, states or cultural identities in any way since I am interested in the dynamism of this period. These divisions are a necessary tool for cross-regional comparisons and using a mixture of archaeological and environmental factors aids in creating units which are more useful for the Early Middle Ages than modern political boundaries. English sites were also plotted to determine spatial clusters and assigned to regions based on this. These can be seen in Figure 3-3.

![Figure 3-2: Map of sites analysed in this thesis, the tissues present and their geo-cultural regional designations.](image)

Site locations were included as decimal degrees latitude and longitude and were garnered from the site reports or any provided maps and archival material. Where
not provided these were determined through Google Maps and Google Earth Pro, the
latter of which also provided altitude estimations for use in the OIPC as described
above (Bowen and Revenaugh, 2003; Google, 2019a, 2019b; Lightfoot and O’Connell,
2016).

![Map of England with regional designations](image)

*Figure 3-3: Map with regional designations in England, *denotes fauna only.*

3.1.3 Environmental data

Knowing the underlying geology for each site is important to investigate links
between geology and dietary isotopes, and for provenancing. I found the underlying
geology for each site through a combination of national geological base maps and the
OneGeology portal (Bedrock Geology of Ireland, 2014; Maps of Denmark, n.d.;
Norway, n.d.). Depending on the source of the geological data, the level of detail varies
greatly, so I added another column – “simplified geology” for easier comparison, with
options of – “Chalk”, “Volcanic/Metamorphic”, and “Other”.
Sites were assigned to environmental categories based on their proximity to a large body of water. If they were 5km or closer to a coast – an easy return trip on foot – they were designated as “Coastal”. The same rule of thumb applies to designations as “Riverine” near a major river or “Lake”. There are more specialised environments such as marine islands, fiords, saltmarsh and fens. Mixed environment types are characterised by combining terms. Sites labelled as “Inland” are further than 5km from the coast, major river or lake, but most are near smaller fresh water sources.

3.1.4 Other contextual data for sites and skeletons

The contextual data for the sites and burials can be found in the digital files themselves (see digital appendices). These categories were chosen to answer the research questions and aims set out in Chapter 1, incorporating different kinds and scales of data to embrace a bio-cultural approach; and the format was chosen for ease of input into R, and to ensure ease of data sharing and reproducibility. For some sites and individuals there are data missing either due to currently ongoing expert analysis (especially on the commercial sites), preservation issues, lack of or poor reporting in original publications, lack of data accessibility and sharing, or language barrier issues on my part for regions where I do not read or speak the language. Every effort was made to make the sites in the United Kingdom and Ireland as complete as possible. I hope that future work will incorporate new contextual data and work with overseas specialists to fill in the gaps.

The difficulties with such metanalyses, data collation and standardisation are not new and are something which others have also encountered with stable isotope data in Britain (Mallet, 2016; Stansbie and Mallet, 2015). Mallet’s (2016) work demonstrates the issues inherent in meta-analyses for example – data standardisation, missing metadata, cross-laboratory and inter-regional comparisons. The statistical and open science aspect of meta-analyses will be discussed in more depth below.

For numerical data, isotope measurements included, values were entered as reported. In most cases these were later standardised to the lowest common denominator (usually 1d.p. for $\delta^{13}$C, $\delta^{15}$N and $\delta^{18}$O values, 4d.p. for $^{87/86}$Sr). For isotopic data, with the exception of strontium, these are reported to one decimal
place as per convention and to avoid excess precision as analytical error for most machines is $\sim 0.2\%$ (Coplen, 2011).

Age, sex, gender and time period were all categories that had to be standardised across the databases for the human analyses. Osteological data (age, sex and pathology) were entered for the skeletons as described by the original investigators, and then standardised. The categories used are described below.

3.1.4.1 Standardising age, sex and gender

Age and sex were largely kept the same as in the original excavation reports. Often sex and age are changed in the tables given in isotope papers with no accounting for the disparity with excavation reports, so I used the original reports for methodological transparency. Five sex categories were used – F, F?, M, M? and U – equating to female, probably female, male, probably male and undetermined, respectively. I kept age as provided in the original reports based on skeletal development. This was done for several reasons despite variation in methods used by different osteologists; firstly, to give traceability and accountability of recording back to original reports. Secondly, as not all skeletons were analysed by myself it was impossible and outside the remit of this work to re-assess all individuals osteologically; thirdly, to mitigate some of these confounding factors of sex and age estimation I created an additional column which I describe in the next paragraph, which is necessarily broader in its age categories to allow for uncertainty in osteological assessments.

Another column “Age Category” was used to standardise age and gender using a biocultural framework (Dufour, 2006; Schutkowski, 2005). I assigned age categories based on skeletal age and sex, gender (based on grave goods) and the types and number of grave goods (if present). This is a modified approach based on Stoodley’s work, which aims to assign age categories which have both a biological and cultural meaning and take account of Early Medieval cultural perceptions of gender, age and rites of passage (Crawford, 2011; Stoodley, 1999, 2000, 2011). I reworked Stoodley’s suggested categories to also consider major biological transitions which are likely to affect stable isotope signatures (e.g. weaning, breastfeeding) (Beaumont et al., 2015,
These categories are sex and gender dependent, where these data were available, due to differences in rites of passage as perceived through grave goods, which are closely tied to the different rates of physical development between the sexes especially during puberty and early adulthood. Early childhood is grouped together, and, if gendered grave goods were placed with sub-adults over the age of ten, this was used to inform the age category as well. Where sex and gender did not match, the gender, grave goods and age of the individual were used to assign an age category. Where good osteological data were not available, I used the very broad categories of “Juvenile” and “Adult”. All age categories are summarised below in Table 3-2.

For sites outside of England, for ease of integration and comparison these categories were also applied, although I acknowledge that whilst the rites of passage seem to be generally similar for the majority of cultural groups in western Europe, these may not be entirely appropriate to use when integrating these cemeteries at their local levels.

<table>
<thead>
<tr>
<th>Skeletal Age Female</th>
<th>Age Category Female</th>
<th>Skeletal Age Male</th>
<th>Age Category Male</th>
<th>Skeletal Age Unsexed/Ungendered</th>
<th>Age Category Unsexed/Ungendered</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-14+</td>
<td>F3</td>
<td>12-14+</td>
<td>M3</td>
<td>10-17</td>
<td>U3</td>
</tr>
<tr>
<td>18-20+</td>
<td>F4</td>
<td>18-20+</td>
<td>M4</td>
<td>18-25</td>
<td>U4</td>
</tr>
<tr>
<td>25/30+</td>
<td>F5</td>
<td>30/40+</td>
<td>M5</td>
<td>25-50</td>
<td>U5</td>
</tr>
<tr>
<td>50+</td>
<td>F6</td>
<td>60+</td>
<td>M6</td>
<td>50+</td>
<td>U6</td>
</tr>
</tbody>
</table>

Table 3-2 – Age Categories used in this thesis for human individuals, based on those of Stoodley (1999, 2000, 2011).

There is certainly interplay between gender roles, these age categories and periodisation to consider. It is generally assumed that Early Medieval gender roles were very prescriptive and, at least for women, remained largely unchanged with Christianisation (except that it was now possible to become a nun) (Bitel, 2002; Foot, 2000; Gilchrist, 1994; Jewell, 2007; Shapland et al., 2015; Stoodley, 1999; Wemple, 1981). Age categories may have shifted through time, and whilst they incorporated data from the historical sources for later periods, they are still problematic post
800AD as there is very little to go on archaeologically for status or rites of passage with the more regulated later churchyard burials (Buckberry, 2007; Buckberry and Cherryson, 2010; Craig-Atkins, 2017).

3.1.4.2 Pathology and stature
Pathology and stature are often missing for individuals in the carbon and nitrogen spreadsheets, as they are frequently recorded in osteology reports as percentages of the whole population studied or referred to in comparison with other cemetery populations, but not always published at an individualised level. Where available stature is recorded in centimetres and pathologies entered as free text.

3.1.4.3 Burial practices
Due to the great variation in burial practice during the period, it was difficult to standardise categories such as grave goods, body position and internment style (Brownlee, 2019; Leggett, 2014; Lucy, 2000; Lucy et al., 2002; O’Brien, 1999; Sayer and Williams, 2009). I recorded the number of grave goods, what they were (as free text) and if any were “foreign” in the carbon and nitrogen spreadsheets. Grave goods were defined as “foreign” based off the excavation report finds assessments and grave catalogues; for instance, if a brooch type was classed as a Continental import versus a locally made imitation of a Frankish or Scandinavian style which would instead be classed as not foreign. This was done alongside body position (e.g. extended supine, prone, crouched, flexed, commingled etc.). I entered the orientation of graves, where known, as cardinal directions with the position of the head as the anchor point.

Internment style was also recorded, but standardisation proved difficult, especially for eighth-eleventh century stone associated burials (e.g. stone lined, pillow or earmuff arrangements) which are highly varied in style, however any coffins, grave markers, or other structural burial provision, and multiple burials were noted. Aside from osteology, I did not include much of this contextually cultural data for burials outside of “England” as this was outside the scope of this thesis. However, I hope that this work will be expanded on in the future for a larger study across Europe.
3.1.4.4  Chronology

As a major focus of this research is on diachronic change, phasing and chronologies of the cemeteries in England was key. Where available, radiocarbon dates were used in conjunction with artefactual typologies to determine the date of the graves, as per Bayliss et al. (2013) and Brownlee (2019). I phased the case study cemetery of Finglesham in more detail than other sites to see if internal chronologies and isotopic trends could be identified at a cemetery scale. The major problem encountered in phasing burials, aside from the lack of grave goods and paucity of radiocarbon dates in post-seventh century sites, is that the leading types from Bayliss et al. (2013) tend to date male burials earlier than female graves in the same cemeteries. This is problematic for many reasons, and, until more radiocarbon dates are available for male graves and unfurnished burials, this problem is unlikely to be rectified any time soon (Bayliss et al., 2013; Brownlee, 2019; Leggett, 2014).

As many sites are lacking in dating evidence, especially when we move beyond the seventh century, the phase boundaries used here necessarily get broader to accommodate this uncertainty. For the backbone of my chronological framework, I took the phases from Bayliss et al. (2013) which separate male and female grave goods and account for peaks and troughs in these gendered funerary provisions up to the seventh century. These are summarised in Appendix K (Bayliss et al., 2013: 460). Since not all graves analysed here fit within the Bayliss et al. (2013) model, I also used Brownlee’s (2019) reassessment for more specific dating of individual graves, especially for Edix Hill and Buckland Dover (Bayliss et al., 2013; Brownlee, 2019: 347–374). Where sites were not included in either Hines et al. (2013) or Brownlee (2019), grave goods, where present, were compared with their leading types and used alongside numismatic and radiocarbon data to assign dates for individual graves. The result was a categorisation of graves and cemeteries into broad phases as well as more specific dates in two columns – “Date” (free text) and “Date Category” (Table 3-3).
I back calls by Brownlee (2019) and others to specifically target unfurnished graves in radiocarbon dating programmes and to “fill the gap” for seventh to eleventh century contexts in our understanding of Early Medieval cemetery chronologies (Bayliss et al., 2013; Buckberry, 2010; Craig-Atkins, 2017; Hills and O’Connell, 2009; Hines et al., 1999; Leggett, 2014; Lucy, 2000).

### 3.1.5 Faunal data collation

I also collated faunal data for carbon and nitrogen stable isotope values for baselines. Similar to the human data, a certain degree of standardisation was necessary for faunal data and follows a similar format as that described above. It also includes age and sex for the animals where available, but this was rare. I took care to note if animals were juveniles as this may affect their isotopic signatures, for example if they were still suckling (Hopkins and Ferguson, 2012; Schurr, 1998). Species were standardised to their common names, with some exceptions: in the cases of some fish classification to species was not possible so the genus, family etc. was used; canids such as domestic dogs and wolves were all grouped together as often they were just listed as “canid” in reports; similarly domestic and wild pigs were grouped as “pig”, and the ovicaprids where separable were kept as “sheep” or “goat” but often left as “ovicaprid”. I used “Species Groups” as a category to aid standardisation, summarised in Table 3-4, as well as the construction of baselines. I also record the type of context for fauna (i.e. settlement or cemetery) to aid in interpretation of results.

<table>
<thead>
<tr>
<th>Date Category</th>
<th>Calendar Years/Time Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Roman/Romano-British/Iron Age 200BC– 450 AD</td>
</tr>
<tr>
<td>B</td>
<td>450-580 AD</td>
</tr>
<tr>
<td>C</td>
<td>580-630 AD</td>
</tr>
<tr>
<td>D</td>
<td>630-690 AD</td>
</tr>
<tr>
<td>E</td>
<td>690-790 AD</td>
</tr>
<tr>
<td>F</td>
<td>790-1000 AD “Viking Age”</td>
</tr>
<tr>
<td>G</td>
<td>1000 AD-1066 AD “Danish” Empire and formation of “England”</td>
</tr>
<tr>
<td>H</td>
<td>1066-1200 AD “Anglo-Norman”</td>
</tr>
<tr>
<td>I</td>
<td>1200 AD+ Middle Ages onwards</td>
</tr>
</tbody>
</table>

*Table 3-3 – Date Categories used in thesis databases.*
<table>
<thead>
<tr>
<th>Species Group</th>
<th>Definition and Species Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Domestic Herbivore</td>
<td>Cattle, Horse (including ponies), Donkey</td>
</tr>
<tr>
<td>Medium Domestic Herbivore</td>
<td>Ovicaprids – Sheep, Goat</td>
</tr>
<tr>
<td>Omnivore</td>
<td>Pigs</td>
</tr>
<tr>
<td>Wild Herbivore</td>
<td>Deer – Roe, Red and Fallow</td>
</tr>
<tr>
<td>Small Mammal</td>
<td>Rodents – Rabbit, Hare, Mice, Rat</td>
</tr>
<tr>
<td>Domestic Fowl</td>
<td>Chickens and Geese</td>
</tr>
<tr>
<td>Other Bird</td>
<td>All waterfowl and other wild birds</td>
</tr>
<tr>
<td>Freshwater Fish</td>
<td>Species which predominantly live in freshwater or estuarine environments incl. catadromous species like eels</td>
</tr>
<tr>
<td>Marine Fish</td>
<td>Species which predominantly live in marine environments incl. salmonids and other anadromous species</td>
</tr>
<tr>
<td>Other Fish</td>
<td>Any unclassified fish</td>
</tr>
<tr>
<td>Carnivore</td>
<td>Canids, Foxes, Cats</td>
</tr>
<tr>
<td>Marine Mammal</td>
<td>Whales, Dolphins, Seals, Walrus etc.</td>
</tr>
<tr>
<td>Other</td>
<td>Any unclassified animals not included in other groups above</td>
</tr>
</tbody>
</table>

Table 3-4 – Species Groups used for fauna.

<table>
<thead>
<tr>
<th></th>
<th>Bone C&amp;N</th>
<th>Dentine C&amp;N</th>
<th>Faunal C&amp;N</th>
<th>Carbonate, Phosphate and Sr</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Entries</td>
<td>4149</td>
<td>931</td>
<td>1799</td>
<td>2046</td>
<td>8910</td>
</tr>
<tr>
<td>Entries for England</td>
<td>2023</td>
<td>735</td>
<td>992</td>
<td>700</td>
<td>4450</td>
</tr>
</tbody>
</table>

Table 3-5 – The total number of entries for each sheet in the databases (digital appendices).
### Table 3-6 – The total number of samples for each human tissue type by date category for the whole dataset, numbers in brackets indicate the total for England.

<table>
<thead>
<tr>
<th>Date Category</th>
<th>Number of Entries Human Bone C&amp;N</th>
<th>Number of Entries Human Dentine C&amp;N</th>
<th>Number of Entries Human Apatite</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>233(187)</td>
<td>0(0)</td>
<td>115(62)</td>
<td>348(249)</td>
</tr>
<tr>
<td>A-C</td>
<td>113(103)</td>
<td>4(4)</td>
<td>27(1)</td>
<td>144(108)</td>
</tr>
<tr>
<td>A-D</td>
<td>51(5)</td>
<td>2(2)</td>
<td>189(36)</td>
<td>242(43)</td>
</tr>
<tr>
<td>A-E</td>
<td>63(1)</td>
<td>75(0)</td>
<td>39(0)</td>
<td>177(1)</td>
</tr>
<tr>
<td>A-F</td>
<td>3(0)</td>
<td>0(0)</td>
<td>8(0)</td>
<td>11(0)</td>
</tr>
<tr>
<td>A-I</td>
<td>20(0)</td>
<td>0(0)</td>
<td>3(0)</td>
<td>23(0)</td>
</tr>
<tr>
<td>A/B</td>
<td>40(38)</td>
<td>4(4)</td>
<td>16(3)</td>
<td>60(45)</td>
</tr>
<tr>
<td>B</td>
<td>537(294)</td>
<td>37(37)</td>
<td>169(89)</td>
<td>743(420)</td>
</tr>
<tr>
<td>B-D</td>
<td>460(166)</td>
<td>11(11)</td>
<td>61(49)</td>
<td>532(226)</td>
</tr>
<tr>
<td>B-E</td>
<td>126(1)</td>
<td>9(1)</td>
<td>13(1)</td>
<td>148(3)</td>
</tr>
<tr>
<td>B-F</td>
<td>38(2)</td>
<td>8(8)</td>
<td>12(8)</td>
<td>58(18)</td>
</tr>
<tr>
<td>B-G</td>
<td>2(0)</td>
<td>4(2)</td>
<td>4(4)</td>
<td>10(6)</td>
</tr>
<tr>
<td>B-H</td>
<td>19(0)</td>
<td>3(0)</td>
<td>0(0)</td>
<td>22(0)</td>
</tr>
<tr>
<td>B/C</td>
<td>253(163)</td>
<td>64(64)</td>
<td>42(32)</td>
<td>359(259)</td>
</tr>
<tr>
<td>C</td>
<td>125(112)</td>
<td>17(17)</td>
<td>12(11)</td>
<td>154(140)</td>
</tr>
<tr>
<td>C-E</td>
<td>28(1)</td>
<td>0(0)</td>
<td>2(0)</td>
<td>30(1)</td>
</tr>
<tr>
<td>C-F</td>
<td>21(4)</td>
<td>3(3)</td>
<td>143(1)</td>
<td>167(8)</td>
</tr>
<tr>
<td>C-G</td>
<td>38(38)</td>
<td>89(89)</td>
<td>0(0)</td>
<td>127(127)</td>
</tr>
<tr>
<td>C-H</td>
<td>1(1)</td>
<td>0(0)</td>
<td>0(0)</td>
<td>1(1)</td>
</tr>
<tr>
<td>C/D</td>
<td>261(248)</td>
<td>68(68)</td>
<td>46(38)</td>
<td>375(354)</td>
</tr>
<tr>
<td>D</td>
<td>126(114)</td>
<td>33(33)</td>
<td>43(43)</td>
<td>202(190)</td>
</tr>
<tr>
<td>D-F</td>
<td>98(50)</td>
<td>11(9)</td>
<td>116(95)</td>
<td>225(154)</td>
</tr>
<tr>
<td>D-G</td>
<td>101(53)</td>
<td>19(19)</td>
<td>105(22)</td>
<td>225(94)</td>
</tr>
<tr>
<td>D-H</td>
<td>1(1)</td>
<td>1(1)</td>
<td>77(77)</td>
<td>79(79)</td>
</tr>
<tr>
<td>D/E</td>
<td>151(59)</td>
<td>4(4)</td>
<td>33(28)</td>
<td>188(91)</td>
</tr>
<tr>
<td>E</td>
<td>29(2)</td>
<td>22(1)</td>
<td>35(1)</td>
<td>86(4)</td>
</tr>
<tr>
<td>E-G</td>
<td>7(3)</td>
<td>0(0)</td>
<td>1(1)</td>
<td>8(4)</td>
</tr>
<tr>
<td>E-H</td>
<td>97(96)</td>
<td>47(0)</td>
<td>1(1)</td>
<td>145(97)</td>
</tr>
<tr>
<td>E-I</td>
<td>31(1)</td>
<td>0(0)</td>
<td>0(0)</td>
<td>31(1)</td>
</tr>
<tr>
<td>E/F</td>
<td>152(39)</td>
<td>13(1)</td>
<td>52(7)</td>
<td>217(47)</td>
</tr>
<tr>
<td>F</td>
<td>268(67)</td>
<td>18(14)</td>
<td>439(18)</td>
<td>725(99)</td>
</tr>
<tr>
<td>F-H</td>
<td>43(9)</td>
<td>2(1)</td>
<td>15(7)</td>
<td>60(17)</td>
</tr>
<tr>
<td>F-I</td>
<td>106(4)</td>
<td>0(0)</td>
<td>12(12)</td>
<td>118(16)</td>
</tr>
<tr>
<td>F/G</td>
<td>206(111)</td>
<td>356(339)</td>
<td>157(53)</td>
<td>719(503)</td>
</tr>
<tr>
<td>G</td>
<td>2(1)</td>
<td>3(3)</td>
<td>4(0)</td>
<td>9(4)</td>
</tr>
<tr>
<td>G-I</td>
<td>122(48)</td>
<td>0(0)</td>
<td>13(0)</td>
<td>135(48)</td>
</tr>
<tr>
<td>G/H</td>
<td>85(0)</td>
<td>0(0)</td>
<td>4(0)</td>
<td>89(0)</td>
</tr>
<tr>
<td>H</td>
<td>32(0)</td>
<td>0(0)</td>
<td>29(0)</td>
<td>61(0)</td>
</tr>
<tr>
<td>H/I</td>
<td>31(0)</td>
<td>2(0)</td>
<td>0(0)</td>
<td>33(0)</td>
</tr>
<tr>
<td>I</td>
<td>29(1)</td>
<td>2(0)</td>
<td>9(0)</td>
<td>40(1)</td>
</tr>
</tbody>
</table>

3.1.6 Standardising oxygen isotope values

The measured oxygen isotope values, whether $\delta^{18}$O_{carb} or $\delta^{18}$O_{phosphate}, were recorded where available and conversions made in separate columns where appropriate. There are a variety of conversion equations available from carbonate to phosphate, and from phosphate to estimated drinking water values, from drinking water to temperature in degrees Celsius, as well as correction equations for measured values.
To compare and contrast different calculations (and see if they alter the identification of outliers), and for ease of comparison with the published results and online isoscape tools, I calculated the following in the spreadsheet (see digital appendices) and used where appropriate:

\[ \delta^{18}O_{\text{carb PDB}} \text{ converted to } \delta^{18}O_{\text{carb VSMOW}} \text{ using (Coplen et al., 1983):} \]

\[ \delta^{18}O_{\text{carb VSMOW}} = \left( \delta^{18}O_{\text{carb PDB}} \times 1.03091 \right) + 30.91 \]

\[ \delta^{18}O_{\text{carb VSMOW}} \text{ to } \delta^{18}O_{\text{PO4 VSMOW}} \text{ using lacumin et al.’s equation (Iacumin et al., 1996):} \]

\[ \delta^{18}O_{\text{PO4 VSMOW}} = \left( \delta^{18}O_{\text{carb VSMOW}} \times 0.98 \right) - 8.5 \]

\[ \delta^{18}O_{\text{carb VSMOW}} \text{ to } \delta^{18}O_{\text{PO4 VSMOW}} \text{ as above with a correction applied (Chenery et al., 2010; Iacumin et al., 1996):} \]

\[ \delta^{18}O_{\text{PO4 VSMOW}} = \left( \left( \delta^{18}O_{\text{carb VSMOW}} \times 0.98 \right) - 8.5 \right) - 1.4 \]

\[ \delta^{18}O_{\text{carb VSMOW}} \text{ to } \delta^{18}O_{\text{PO4 VSMOW}} \text{ using updated equations from Chenery et al. (Chenery et al., 2012):} \]

\[ \delta^{18}O_{\text{PO4 VSMOW}} = \left( 1.0322 \times \delta^{18}O_{\text{carb VSMOW}} \right) - 9.6849 \]

\[ \delta^{18}O_{\text{dw}} \text{ calculated using a modified Levinson equation from Chenery et al. via Daux (Chenery et al., 2010; Daux et al., 2008; Levinson et al., 1987; Longinelli, 1984; Luz et al., 1984):} \]

\[ \delta^{18}O_{\text{dw}} = \left( \delta^{18}O_{\text{PO4 VSMOW}} - 19.4 \right) / 0.46 \]

\[ \delta^{18}O_{\text{dw}} \text{ calculated directly from } \delta^{18}O_{\text{carb VSMOW}} \text{ (Chenery et al., 2012):} \]

\[ \delta^{18}O_{\text{dw}} = 1.59 \times \delta^{18}O_{\text{carb VSMOW}} - 48.634 \]

Temperature in Degrees Celsius from both of the \( \delta^{18}O_{\text{dw}} \) results (via Levinson and Chenery) was calculated using the following formulae (Rozanski et al., 1992, 2013):

\[ \delta^{18}O_{\text{dw}} = \left( 0.59 \pm 0.09 \right) T - 14.35 \]

\[ T/\text{degC} = \left( \delta^{18}O_{\text{dw}} + 14.35 \right) / 0.59 \]
For simplicity $\delta^{18}$O$_{PO4}$ \textit{vsmow} either as measured or calculated through the Chenery 2012 equation will be reported as $\delta^{18}$O$_{phosphate}$ (SMOW) or simply as $\delta^{18}$O unless otherwise specified, with the rest of the data, raw and converted, reported in the appendices.

$\Delta^{18}$O$_{dw-MAP}$ was also calculated for each sample with $\delta^{18}$O values available from both of the drinking water equations above. This was done as a simplistic measure to complement traditional visual and statistical methods for the identification of outliers/migrants using $\delta^{18}$O values by calculating the difference between the theoretical $\delta^{18}$O$_{MAP}$ values obtained from the OIPC and the $\delta^{18}$O$_{dw}$ values calculated from human tooth enamel. This will be discussed in more detail in later chapters, but the equation is extremely simple:

$$\Delta^{18}\text{O}_{dw-MAP} = \delta^{18}\text{O}_{dw} - \delta^{18}\text{O}_{MAP}$$

3.2 Statistical analyses, software and reproducibility

A priority for this research was to undertake statistical analyses which were appropriate to the datasets at hand, and which would better characterise and handle the difficulties and uncertainties inherent in archaeological data. Many statistical tests and models have been developed in and for fields that have the ability to pre-plan experiments and sample sizes. Archaeological investigations by their very nature rarely have these luxuries. As such archaeological data often have large biases (e.g. large differences in sample sizes between groups), which is the case with the data here. These biases would lead to the violation of assumptions for common statistical approaches such as ANOVA and student’s t-tests (e.g. assumption of equality of variance across groups) (Zuur et al., 2010). Additionally, my sampling design was nested with varying levels of geographical designation (European Region, region within England, Environment type, Simplified Geology, Site), varying numbers of sexes, genders and age groups as well as funerary treatments and date categories represented across these locales. Frequentist approaches tend to perform poorly with these kinds of unbalanced data structures. However, Bayesian and exploratory data analysis (EDA) get around some of these issues.
EDA is more of a state of flexibility than a protocol per se, which avoids the proliferation of type I and type II errors and other such problems, reducing the likelihood of making false archaeological interpretations (Tukey, 1977: 806; Zuur et al., 2010). EDA does not demand "probability, significance or confidence" so avoids many of the grievous statistical sins (Tukey, 1977: 794). Bayesian thinking is preferable to frequentist approaches as it is more flexible and less fragile; it copes with non-parametric data and uncertainty without having to violate assumptions and commit other statistical sins (Kruschke, 2013, 2014; Kruschke and Liddell, 2018; Lavine, 2019; McElreath, 2018: 2–4). Therefore, I adopted a Tukey-style EDA framework and Bayesian thinking in my analyses. I explore my data graphically first before undertaking hierarchical clustering analysis, simple linear regressions and Bayesian tests where appropriate (McElreath, 2018; Tukey, 1977; Zuur et al., 2010). The approach I have adopted can be broadly summarised as “New Statistics” which is underscored by using Open Science practices. It embraces both explorative and planned statistical methods so long as the authors are open about what they are doing and why (Calin-Jageman and Cumming, 2019; Collaboration, 2015; Kruschke and Liddell, 2018). EDA and “New Statistics” allow researchers to be “actively incisive rather than passively descriptive, with real emphasis on the discovery of the unexpected” (Tukey, 1977: lxii).

Furthermore, no p-values will be reported in this thesis as per the American Statistical Association (ASA) guidelines which encourage statistical approaches like those used here, integrating EDA and Bayesian thinking alongside cautious use of frequentist approaches (Calin-Jageman and Cumming, 2019; Gannon et al., 2019; Lavine, 2019; Wasserstein et al., 2019; Wasserstein and Lazar, 2016). The association states “[i]n sum, “statistically significant” – don’t say it and don’t use it” (Wasserstein et al., 2019; Wasserstein and Lazar, 2016).

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 freely available as part of the digital appendices and will be made available on my GitHub after examination - https://github.com/samlegs22/PhD_thesis/. Maps were created using the Free and Open Source QGIS version 3.10 unless otherwise attributed (QGIS, 2020).
My analytical workflow was to first assess normality in datasets using qqplots, using a combination of base R functions, and R packages “ggplot2” and “qqplotr” (Aldor-Noiman et al., 2013; Almeida et al., 2020; R Development Core Team, 2017; Thode, 2002; Wickham, 2019). Few kinds of data in my datasets were normally distributed, further demonstrating the need for a “New Statistics” approach (see Appendix C). I then visualised and explored the data with a range of plots including scatterplots (both 2D and 3D), violin plots, ridge plots, and bagplots. I used R packages “ggplot2”, “ggridges”, “scatterplot3d” and the `geom_bag` function (Ligges et al., 2018; Marwick, 2018; Wickham, 2019; Wilke, 2020). The importance of using different kinds of visualisation techniques is typified by Anscombe’s quartet and the Datasaurus Dozen\(^7\) (see R package “datasauRus” for examples) (Anscombe, 1973; Locke et al., 2018; Matejka et al., 2016; Matejka and Fitzmaurice, 2017).

For analysis and visualisation of singular isotope data (e.g. \(\delta^{13}\)C data by itself), arranged by another categorical variable (e.g. simplified geology), I used violin and ridge plots instead of boxplots (Figure 3-4). This is because boxplots can misrepresent the data by showing the summary statistics but not the shape of the distribution and can lead to false impressions of similarity in datasets whereas violin and ridge plots (here coloured by quartile) can simultaneously represent these summary statistics and shape of the distributions (Anscombe, 1973; Matejka et al., 2016; Matejka and Fitzmaurice, 2017). Violin plots are better at including point jitters to display outliers and individual data points where ridge plots show summary statistics in an easier format.

---

\(^7\) Anscombe’s quartet and the Datasaurus Dozen are groups of datasets (four and twelve respectively) which have almost identical summary/descriptive statistics (mean, median, mode, variance, IQRs etc.) which have very different distributions. They are used to illustrate the importance of plotting graphs and choosing the correct type of graph for your data, before undertaking statistical analyses and model construction (see [https://www.autodesk.com/research/publications/same-stats-different-graphs](https://www.autodesk.com/research/publications/same-stats-different-graphs)) (Anscombe, 1973; Locke et al., 2018; Matejka et al., 2016; Matejka and Fitzmaurice, 2017).
Scatterplots use Cartesian coordinates to display data in two or three-dimensional space, showing the relationship between variables. I often visualise these with marginal distribution or box plots to show the density, outliers or summary statistics of each variable, using the R package “ggExtra” and its function ggMarginal (Figure 3-5) (Attali and Baker, 2019).

Bagplots are bivariate versions of boxplots and are essentially an enhanced two-dimensional scatterplot. They show the depth median (the point with the highest possible Tukey depth) which is roughly analogous to the univariate median and visualised as a cross. Then there is a darker shaded polygon around the cross that encloses 50% of the points around the depth median called the 'bag', analogous with the box in a box plot. Around the bag is another lighter shaded polygon enclosing a region three-times the size of the bag called the 'loop', which is analogous to the whiskers of the box plot (Figure 3-6). Any points outside the bag and loop are considered outliers and not automatically visualised (Marwick, 2018; Rousseeuw et al., 1999; Wickham and Stryjewski, 2012).
I undertook simple linear regressions to look at the strength of relationships between numeric variables. These were done using R packages “ggplot2” and “ggpmisc”. More details are alongside analyses in Chapters 5-8 (Anscombe, 1973; Aphalo and Slowikowski, 2020; Kassambara, 2018; Wickham, 2019).

I used BEST (Bayesian Estimation Supersedes the t-test) tests to compare between groups, these were run with R package “BEST” (Kruschke, 2013). The BEST test uses Markov-chain Monte-Carlo (MCMC) sampling to generate posterior predictive distributions for group data. In Bayesian statistics posterior predictive distributions (PPDs), and therefore the means of these distributions, are distributions of possible unobserved values which have been predicted based on the observed or ‘real’ data put into the model (Kruschke, 2013, 2014). An important point is that the results are drawn from the PPD generated from the MCMC and not the inputted data directly. The key aspects of the output are shown below in Figure 3-7.
Figure 3-7: Example BEST test output with explanatory notations.

What aids us in group comparisons are their respective PPD means shown in the top left, and the mean difference of means (referred in text as MDM) which is the average of the group means from the PPD. If the MDM graph (highlighted by the red box in Figure 3-7) spans zero (on the x axis underneath the distribution, also shown helpfully by green text in the graphic) the two groups were found by the model to have the same mean, at least some of the time, so we cannot be confident in any difference between their means. Their PPD standard deviations and difference between these are to be taken the same way. This highlights if the two groups might have large differences in their distributions. The BEST test also looks at the normality of the two groups combined (bottom left) and gives the effect size of any differences between the group means (bottom right) showing the strength and directionality of any trend.

Given the nested nature of the data, I undertook hierarchical clustering 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 done
using Ward’s hierarchical agglomerative clustering method and the Ward2 algorithm (Kassambara, 2017; Murtagh and Legendre, 2014; Ward, 1963). I cross-validated this unsupervised machine-learning (UML) approach by using 32 different indices and visualising the clusters in two- and three-dimensional scatterplots as appropriate. The indices are listed in full in Appendix F, they are a mixture of various statistical and graphical methods for determining the optimal number of clusters, 30 of which are automatically computed as part of the “NbClust” package, and the other graphical indices I generated using a combination of “NbClust” and “factoextra” packages in R (Charrad et al., 2014; Kassambara, 2017; Kassambara and Mundt, 2017). All 32 indices are used for every UML iteration, and the majority rule adhered to (optimal number of clusters determined by agreement of the highest number of indices out of 32) to avoid user determination, unless it did not match the data structure or there was no clear agreement between indices (which was only in one instance see Chapter 6 for further discussion). The pre-sets for all indices were kept (generally this also means a 95% CI if CI’s were used by the index, see Appendix F and “NbClust” documentation for mathematical details), and the algorithm run for the clustering method used (Ward2 hierarchical). I used a combination of base R functions, the A2R function, and packages “ggdendro”, “ape”, “factoextra”, “cluster”, “NbClust” and “ggplot2” (see digital appendices for code) to run the hierarchical clustering and visualize the outputs (Charrad et al., 2014; de Vries and Ripley, 2016; Grolemund and Wickham, 2020; Kassambara and Mundt, 2017; Kaufman and Rousseeuw, 2009; Lamarange, 2006; Maechler et al., 2019; R Development Core Team, 2017; RStudio Team, 2019; Wickham, 2019). The results of the hierarchical clustering are first visualised with a dendrogram which shows the structure of the data and proximity of individuals to one another within this structure. Then the clusters are used to colour scatterplots for each of interpretation of the isotopic niches these represent. The clusters are 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 from different geo-cultural regions.
Finally, in Chapter 8, I use the DetectingDeviatingCells (DDC) algorithm to detect outlying cells in my case study data. This approach uses the entirety of the data matrix to determine if certain cells are higher or lower than expected given the rest of the dataset. It therefore tells us if certain individual burials are outliers for one or more metrics, given the data for their region (here Kent and East Sussex) or their cemetery (Finglesham). It produces a graph called a cell map (see Figure 3-9). Red cells are higher than predicted values, blue cells are lower than predicted, yellow are as predicted, with orange and purple forming a scale between the extremes. White cells have missing values for that variable. Black or grey dots next to the individual row highlight whole rows which are outliers in the dataset due to a high number of outlying cells (here columns as I rotated the cell maps for easier viewing). The algorithm can only be used on numeric data and excludes individuals with over 50% missing data, and numeric variables which have only a few different observed entries (i.e. not much variation in that variable). This was done using the R package cellWise (Raymaekers et al., 2020; Rousseeuw and Bossche, 2018).
In this chapter I have detailed my meta-analytical study design, and in the following chapter I cover my laboratory materials and methods for stable isotope analyses I undertook on human and animal tissues which were incorporated into the larger meta-analyses.
4 Primary Isotope Analysis Sampling, Materials and Methods

This chapter covers the primary isotope analyses undertaken – sampling strategies and sample collection, chemical processing and stable isotope mass spectrometry.

4.1 Primary analysis sampling strategy

To complement and expand upon the databases described in Chapter 3, sites and individuals were selected following criteria detailed below. At all sites the fauna and human individuals studied represent a subsample of each burial population. Stable isotope analyses were carried out to improve, where possible, faunal baselines in geographical areas where data is absent or poor, as well to extend and expand the geographical and chronological scope of the published human data by including sites and individuals which can help us better characterise the people living in Early Medieval England and improve resolution of these datasets.

4.1.1 Site selection

The primary factors for site selection were location and chronology. Mallet’s (2016) work has highlighted several regions and centuries which are lacking in both human and faunal data, and I adjusted my sampling strategy to reflect this. Counties with a scarcity of data were identified: Bedfordshire, Buckinghamshire, Cheshire, Cumbria, Gloucestershire, Hertfordshire, Kent, Lancashire, Northumberland, Surrey, Sussex, Warwickshire and Yorkshire. Some of these regions have well-known problems with skeletal preservation (the north, and west of the Pennines especially), whilst others, until recently, have had a scarcity of modern excavations. Some regions are dominated by data from only one or two sites – for example Raunds Furnells in Northamptonshire dominates that region due to several stable isotope studies being conducted on the population – so I also aimed to sample more sites and individuals in these regions to broaden the data available in these areas (Beaumont et al., 2018; Dunne et al., 2019; Haydock et al., 2013).

Sites from the eighth to twelfth centuries AD have limited isotopic data compared to the more heavily sampled third to seventh centuries. A mixture of sites from across the second half of the first millennium AD was therefore a priority with some sites such as Priory Orchard Godalming in Surrey having burials spanning most of the
period. Similarly, well-dated sites, especially from the later centuries are rare, so well-dated sites (from radiocarbon and/or typology) with contextual information for the burials available were chosen to allow for ease of analysis.

I initially set a minimum number of individuals (mni) per cemetery (n=30) as a screening variable; however, access to collections and the availability of larger sites proved difficult so this criterion became flexible, with an mni of n=10 largely being adhered to. There are a few sites which are exceptions, due to poorer than expected skeletal preservation or retention of material in collections, high regional significance or other sampling strategies which opportunistically allowed them to be simultaneously sampled for isotopic analysis. Ultimately accessibility and approval for destructive analysis proved to be the biggest barrier, but a good selection of sites and individuals was still achieved given the rest of the sampling criteria. I therefore could not fully address the paucity of funerary or stable isotope work in certain regions (the west of England especially), but the sites chosen below (see Table 4-1) have made a significant contribution to the landscape of burial evidence and isotopic variability in Early Medieval England.

4.1.2 Individual selection

The selection of individuals was based on information from site reports as well as the condition of the skeletons at the point of sampling in collections. As several sites were analysed through collaborations with various projects and institutions, some of the individuals were selected to compromise with these other research agendas. Osteological analysis either completed or substantially underway by other specialists was a requirement to maximise data about the skeleton and limit extra analysis or waiting time to obtain these data.

Adults were preferentially sampled with some late sub-adults being chosen due to cultural perceptions of adulthood in the Early Middle Ages, and a small number of children were also included where other sampling priorities dictated choice of individual (i.e. collaborations with the After the Plague Project, Museum of London Archaeology Northampton and University of Roehampton); however for certain statistical analyses children and other groups were excluded (see Chapters 6-9).
Where possible individuals with both suitable ribs and surviving teeth were preferred, unless other research objectives or isotopic analyses being undertaken by other parties meant they were included.

Good bone and enamel preservation were also key factors for selection. Individuals whose bones might have low collagen yields or tissues otherwise affected by diagenesis, and thus might complicate the interpretation of results, were avoided. Where I did the sampling personally (as opposed to osteologists selecting samples for me) this was assessed visually and physically by the texture and appearance of the bone (e.g., was it crumbling or discoloured, were there significant signs of microbial activity, were there any signs of petrification in the bones etc.). Both males and females were included irrespective of grave provisioning so long as they met the above criteria.

Some individuals with one or more tissues already analysed were chosen using the above criteria for the other tissues to complement the existing data e.g. Water Lane Melbourn was sampled for dentine, where the ribs had already been analysed by Emma Hannah (2015, 2019).

Inter-laboratory variability was a concern not only in these cases where I was doing complementary analyses on the same individuals sampled by others, but also for the larger meta-analyses as comparing across laboratories with their varying techniques and machinery can add to the variability of these datasets and make comparisons across all isotopes and tissues difficult. However, it was nearly impossible to conduct an inter-laboratory variation analysis here as not all laboratories have run comparable samples (either of the same species and date, or aliquots of the same sample) to conduct robust comparisons, a problem also encountered by Mallet and others in their analyses; to properly quantify inter-laboratory variation institutions must agree to rigorous re-testing of the same samples and provide all the necessary methodological and machine data (Jay, 2005: 162–175; Mallet, 2016: 108–110; Pestle et al., 2014; Stansbie and Mallet, 2015). Most laboratories do run internationally recognised standards alongside their own internal standards (see below in section 4.4) however not all publish the results of these on their website or alongside the archaeological IA data, this is particularly true for apatite analyses (both bone and
Jay (2005) conducted her own inter-laboratory and inter-equipment study, also considering variations between skeletal elements and collagen extraction procedures. She found that none of the factors she considered (lab, skeletal element, machine, variation across replicates or extractions) showed variation significant enough beyond normal analytical error considerations (approx. 0.2‰) to cause concern, and therefore considered it appropriate to allow comparisons for collagen (bone and tooth) across labs, sites, skeletal elements etc. so long as collagen quality indicators (see below) were adhered to (Jay, 2005: 165–172). A more recent inter-laboratory study for archaeological IA looked at both collagen and hydroxyapatite in bone (Pestle et al., 2014). They found that for collagen differences between laboratories averaged at 0.2‰ for $\delta^{13}C_{\text{coll}}$ and 0.4‰ for $\delta^{15}N_{\text{coll}}$. They considered any inter-laboratory variation so small as to not be a cause for concern, reiterating Jay’s (2005) findings. For apatite the findings were more varied with average pairwise laboratory differences found to be 0.6‰ for $\delta^{13}C_{\text{apatite}}$ and up to 2.0‰ for $\delta^{18}O_{\text{apatite}}$. Pestle et al. (2014) concluded that diagenesis of bone apatite was unlikely to be the source of this variation as they found that intra-laboratory variation was minimal compared to inter-laboratory differences. The source of this variation is from two main sources. Differences in pre-treatment protocols are a small contributor to variation, but the primary driver of variation in apatite values across laboratories seems to be instrumentation and/or standardization procedures (Garvie-Lok et al., 2004; Koch et al., 1997; Pestle et al., 2014). However, they hypothesised that inter-laboratory differences may be less for enamel due to it having a slightly different molecular structure to bone apatite and therefore being more diagenetically robust (see Chapter 2). They suggest these bone apatite findings should be used as a starting point for enamel interpretations, but similar studies need to be conducted for this tissue (and were outside the scope of this thesis) (Pestle et al., 2014). At present there has not been a similarly robust study for strontium as it is less common, mostly due to expense of both the reagents and machinery, however I hope in coming years a similar studies may be conducted. The main message of these inter-laboratory comparisons is to be cautious and not over-interpret small variations in isotope values. This was a main consideration in using EDA as one of the primary data analysis methods here and in interpretations throughout, particularly in Chapter 7.
4.1.3 Biological specimen selection and collection

Garrod Laboratory SOPs (standard operating procedures) were followed for sampling, and with the exception of Edix Hill, Lower Luton Road Harpenden and sites provided by MOLA Northampton (Southam, Stanton, A5 M1 Site H, Whitehall Farm and Ketton Quarry) I selected all bones, and teeth at the collections that housed them. Edix Hill was sampled at the McDonald Institute for Archaeological Research, Cambridge, in a collaborative effort with Dr Sarah Inskip and Alice Rose from the After the Plague Project to select individuals suitable for both our projects and take samples for both aDNA and isotope work. The skeletons were brought to Cambridge from deep store thanks to the Cambridgeshire County Council. Archaeology South East sent tissues for the Harpenden individual sampled fortuitously as it is the only skeleton definitively dated to the Early Medieval period in the county. Chris Chinnock from MOLA Northampton selected individuals and specimens thereof with guidance from myself as per above criteria and couriered them to the McDonald Institute for processing.

Ribs were preferred for bone specimens, with long bones as the second choice. In some collections the torso portion or whole post-cranial skeleton had been lost since excavation, and in these cases just teeth were sampled (e.g. Newnham College) (Hedges et al., 2007; Lucy et al., 2009). Permanent second premolars or second molars were preferred due to their similarity in development timings (see Table 2-1 above) and because they represent a post-weaning signature in both enamel and dentine (Beaumont et al., 2015; Evans et al., 2012; Scheid, 2007: 326–334). Some individuals did not have teeth suitable for sampling (e.g. could not easily extract the tooth, or too carious or worn on inspection), some had other teeth taken to fulfil other research project objectives, but the priority was to limit damage to skeletons, so if a tooth could not be easily extracted, only bone was taken.

4.2 The sites and their historical contexts

Cemeteries and the people within them are key to answering the questions raised in this thesis. The study of Early Medieval cemeteries has a long history, with notable works mentioned throughout this thesis. To determine if there is change in diet over time, chronology is key, and a selection of individuals from cemeteries dating from
the end of the Roman occupation of Britain up to the Anglo-Norman period was imperative. Therefore, many of the cemeteries studied here span several centuries, and individuals analysed as part of the primary isotopic work range predominantly from the sixth to the eleventh century AD.
<table>
<thead>
<tr>
<th>Site</th>
<th>County</th>
<th>Collection</th>
<th>Century</th>
<th>Bone Samples</th>
<th>Dentine Samples</th>
<th>Enamel Samples</th>
<th>Fauna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kirkdale</td>
<td>Yorkshire</td>
<td>University of Sheffield</td>
<td>7m-11m</td>
<td>18</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Edix Hill (Barrington A)</td>
<td>Cambridges</td>
<td>Cambridgeshire County Council</td>
<td>6m-7m</td>
<td>44</td>
<td>37</td>
<td>38</td>
<td>0</td>
</tr>
<tr>
<td>King’s Garden Hostel</td>
<td>Cambridges</td>
<td>Duckworth Laboratory</td>
<td>7m</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Finglesham</td>
<td>Kent</td>
<td>Duckworth Laboratory</td>
<td>6m-7m</td>
<td>45 (44)</td>
<td>40</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Collingbourne Duc’s (1978)</td>
<td>Wiltshire</td>
<td>Wiltshire Museum, Devizes</td>
<td>5m-7m</td>
<td>20</td>
<td>14</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>Mill Hill, Deal</td>
<td>Kent</td>
<td>Dover Museum</td>
<td>6m-7m</td>
<td>23</td>
<td>24</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>Buckland Dover (1997)</td>
<td>Kent</td>
<td>Canterbury Archaeological Trust</td>
<td>6m-7m</td>
<td>15</td>
<td>14</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Holborough</td>
<td>Kent</td>
<td>Duckworth Laboratory</td>
<td>6m-7m</td>
<td>19</td>
<td>16</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>Stanton</td>
<td>Suffolk</td>
<td>MOLA Northampton</td>
<td>4m-8m</td>
<td>20 (19)</td>
<td>19</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>A5 M1 Site H</td>
<td>Bedfordshire</td>
<td>MOLA Northampton</td>
<td>7m</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Southam</td>
<td>Warwickshire</td>
<td>MOLA Northampton</td>
<td>7m-9m</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>0</td>
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<tr>
<td>Priory Orchard Godalming</td>
<td>Surrey</td>
<td>University of Roehampton</td>
<td>8m-12m</td>
<td>93</td>
<td>0</td>
<td>0</td>
<td>16</td>
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<tr>
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<td>Cambridges</td>
<td>Cambridge Archaeological Unit</td>
<td>7m-8m</td>
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<td>0</td>
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<tr>
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<td>Cambridges</td>
<td>Duckworth Laboratory</td>
<td>7m-8m</td>
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<td>3</td>
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<td>0</td>
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<tr>
<td>Water Lane Melbourn</td>
<td>Cambridges</td>
<td>Cambridgeshire County Council</td>
<td>6m-7m</td>
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<td>28</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lower Luton Road, Harpenden</td>
<td>Hertfordshire</td>
<td>Archaeology South-East, Essex Office</td>
<td>7m</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Whitehall Farm, Nether Heyford</td>
<td>Northamptonshire</td>
<td>CLASProject and MOLA Northampton</td>
<td>5m-7m</td>
<td>6</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ketton Quarry</td>
<td>Rutland, Leicestershire</td>
<td>MOLA Northampton</td>
<td>10m-11m</td>
<td>19</td>
<td>14</td>
<td>14</td>
<td>9</td>
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<tr>
<td>TOTAL</td>
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<td>827 (826)</td>
<td>348 (346)</td>
<td>243</td>
<td>200</td>
</tr>
</tbody>
</table>

Table 4.1 - Sites and number of samples per tissue type processed for primary stable isotope analysis, including duplicate and failed samples. One rib sample from Finglesham failed to produce collagen (grave 18), and one individual was sampled twice from Stanton (individual 35). All samples outside the failed rib passed quality control procedures (detailed below), this included yielding enough collagen to measure as well as satisfactory %C and %N content, and C:N ratios. In some runs there were instrumentation problems so further aliquots were re-run, details of which runs, dates and the issues can be found in the Digital Appendices.
4.3 Sample selection – fauna

Where fauna was available from a site or a nearby settlement it was included to establish a baseline for the local area. For many of the included cemeteries, these fauna samples are the first in the region (for any period) to be analysed for stable isotopes so establishing good baselines was essential. However, this was not always possible due to site type, preservation, lost archives, excavation techniques and other factors.

Faunal samples were selected on availability and frequency of species at a site. A range of herbivores, omnivores, carnivores and birds, both wild and domesticated, were sought. I also wanted to analyse fish, both freshwater and marine, however none were available for sampling for the sites here due to the factors mentioned above. Bones from well-defined non-grave contexts were preferred but not always available. Both bones from intrusive grave contexts and purposeful depositions were analysed where no other nearby well-provenanced material was available. Ideally faunal remains which had associated radiocarbon dates were chosen to aid interpretations and associations with the human remains. For each context care was taken to avoid double-sampling of individuals by selecting the same element, or by choosing individuals by age. Identification of element, species and age was done by Leah Damman at the Grahame Clark Laboratory for Zooarchaeology at the University of Cambridge, and then samples selected from her assessments.

<table>
<thead>
<tr>
<th>Site</th>
<th>Fauna Count</th>
<th>Species Represented</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collingbourne Ducis</td>
<td>1</td>
<td>cattle</td>
</tr>
<tr>
<td>Ketton Quarry</td>
<td>9</td>
<td>4x equids, 1x ovicaprid, 2x cattle, 1x roe deer, 1x pig</td>
</tr>
<tr>
<td>Kirkdale</td>
<td>4</td>
<td>3x ovicaprids, 1x cattle</td>
</tr>
<tr>
<td>Priory Orchard, Godalming</td>
<td>16</td>
<td>7x cattle, 7x ovicaprids, 2x pigs</td>
</tr>
<tr>
<td>Stanton</td>
<td>7</td>
<td>1x canid, 1x goose, 4x ovicaprids, 1x red deer</td>
</tr>
</tbody>
</table>

*Table 4-2: Summary of species analysed per site.*
4.4 Stable isotope analysis

The principles and applications of stable isotope analyses were detailed in Chapter 2. The laboratory methods and sample processing undertaken are detailed here with the relevant SOPs for each process included in Appendix B. After initial specimen collection all tissues were transported to the Dorothy Garrod Laboratory for Isotopic Analysis at the McDonald Institute for Archaeological Research, University of Cambridge where they were prepared. Isotope mass spectrometry for both collagen and enamel was conducted in the Godwin Laboratory, Department of Earth Sciences, University of Cambridge, with assistance from Catherine Kneale and James Rolfe. The preparation of all tissues from Edix Hill (Barrington A) (see Table 4-1 above) was shared equally with Alice Rose as part of the After the Plague Project to maximise individuals analysed and collaboration on re-analysis of the skeletal material. The data were separately analysed within our doctoral theses after initial agreement on quality indicators. Tooth enamel from the sites of Stanton, Suffolk and Buckland Dover, Kent was prepared by Estelle Praet as part of her MPhil in Archaeological Science laboratory coursework project under my supervision.

4.4.1 Collagen preparation

Collagen was extracted from bone and dentine samples following a modified Longin method (see SOP3) (Longin, 1971; Privat et al., 2002; Richards and Hedges, 1999).

If samples were above 1.0g they were cut by hand using a diamond cutting wheel attached to a handheld drill to obtain fragments of between 0.5-1.0g. The fragments were then cleaned by shot blasting.

Bone was then demineralized in 8ml of 0.5M HCl(aq.) at 4°C for five to ten days dependent on the bone and rinsed three times in distilled water.

The demineralized bones were then gelatinized in approximately 8ml of pH3 water (adjusted with HCl(aq.)) at 75°C for 48 hours. The liquid portion containing the collagen protein was then separated using filtration by Ezee filter and frozen at -20°C until solid and transferred to -80°C for a minimum of four hours.
Samples were then lyophilised for between one to five days, with the final material containing collagen and possibly some acid salts. The collagen yield (final lyophilised product weight compared to the original bone fragment mass) was then calculated at this stage. Low yields (<2%) were not sent for analysis on the mass spectrometer as it was unlikely these samples produced well preserved collagen.

0.8±0.1mg of collagen was weighed into tin capsules in triplicate, with each replicate from the top, middle and bottom third of the lyophilised collagen column respectively.

Analyses were conducted using an automated elemental analyser coupled in continuous-flow mode to an isotope-ratio-monitoring mass-spectrometer (see Figure 4-1 below). Stable isotope concentrations are measured as the ratio of the heavier to the lighter isotope. These values are reported relative to an internationally defined scale - VPDB (δ13C) and AIR (δ15N). Where δ15N_{AIR} = \left[\frac{^{15}/^{14}N_{sample}}{^{15}/^{14}N_{AIR}}\right]-1, and δ13C_{VPDB} = \left[\frac{^{13}/^{12}C_{sample}}{^{13}/^{12}C_{VPDB}}\right]-1 (Brown and Brown, 2011; Coplen, 2011; Hoefs, 2009; Price and Burton, 2012). Analytical error (1σ) for all collagen samples is ±0.20‰. The isotopic standards used are IAEA standard of caffeine for carbon and nitrogen; in-house standards of nylon, alanine, protein 2 and EMC (Elemental Microanalysis caffeine) for carbon, nitrogen and atomic C/N ratios.

![Schematic diagram of Costech ECS 4010 elemental analyser (Valencia, CA, USA), Finnigan Delta V mass spectrometer (Bremen, Germany) coupled system courtesy of T.C. O'Connell.](image-url)
4.4.1.1 Quality control and assessment

When data is received back from the mass spectrometers it is assessed for collagen preservation (in the case of C&N on bone and dentine) as well as internal quality control for machine function and preparation procedures. This is done through comparison with laboratory and internationally accepted standards. Laboratory standards should be within ±0.1‰ of the expected value, and all samples and standards should have a standard deviation of 0.2 or less between runs. The amplitude peaks of the samples are also checked against the reference gas peaks, then checked for protein composition and preservation by using the %C (acceptable >13%) and %N (acceptable >4-5%) in each sample and calculating the atomic C/N ratio:

\[ \text{C/N ratio} = \left( \frac{\text{Amt } \%C}{\text{Amt } \%N} \right) \times \left( \frac{14}{12} \right) \]

The accepted C/N ratio for bone and dentine samples is between 2.9-3.6, with the theoretical value being 3.17, %C yield should be above 13% and >4.8% for %N yields, following the accepted indicators for good collagen preservation (Ambrose, 1990; DeNiro, 1985; Ubelaker et al., 1995).

4.4.2 Enamel preparation Balasse method

Tooth enamel powder was prepared for stable isotope analysis of bioapatite (carbonate) following the Balasse method (see SOP 19 in Appendix B) (Balasse et al., 2002).

Teeth were cleaned using a toothbrush first to remove dirt and other adhering material. Scalpel blades were used to remove dental calculus and placed in clean Eppendorf tubes. The outer surface of the tooth enamel was then cleaned with a drill bit to remove any further traces of adhering material.

Enamel powder was collected from cleaned teeth using a diamond tipped drill bit onto weighing paper, taking care not to include any dentine in the sample, and then transferred into Eppendorf tubes. A minimum of 2-4mg of enamel can be sent to the gas bench, and a maximum of 15mg can be chemically treated, so between 6-15mg was drilled where possible. If there were chunks of enamel in the sample, these were
then crushed using a cleaned agate pestle and mortar and passed through a 90-micron sieve.

Enamel powder and laboratory standards were then treated with 0.1ml per mg of powder of 2-3% NaOCl(aq.) for 24h at 4°C and rinsed, vortexed and centrifuged five times in distilled water.

To remove secondary carbonates samples were then treated with 0.1ml per mg of powder of 0.1M acetic acid(aq.) for 4 hours at room temperature, then rinsed, vortexed and centrifuged five times with distilled water.

Once all liquid is removed samples were frozen at -20°C for 1 hour and transferred to -80°C for a minimum of two hours, and then lyophilised for between 2-4 hours.

The resulting powder was weighed to establish loss of enamel during pre-treatment (40-50% loss in sample weight is expected). Between 2-4mg of treated enamel powder was transferred into glass vials sealed with a screw cap holding a septa and PCTE washer to create a vacuum seal.

The vacuum sealed glass vials containing the enamel were reacted with 10% orthophosphoric acid at 90°C using a Gas Bench II coupled to a Delta V mass spectrometer for isotopic analysis.

The enamel carbonate isotope values are reported in units permille with reference to the VPDB standard calibrated through the NBS19 standard for carbon $\delta^{13}\text{C}_{\text{VPDB}} = \left[ \left( \frac{^{13}\text{C}_{\text{sample}}}{^{13}\text{C}_{\text{VPDB}}} \right) - 1 \right] \times 1000$, and with reference to VSMOW (Vienna Standard Mean Ocean Water) for $\delta^{18}\text{O}$ using internal standards such that $\delta^{18}\text{O}_{\text{VSMOW}} = \left[ \left( \frac{^{18}\text{O}_{\text{sample}}}{^{18}\text{O}_{\text{STANDARD}}} \right) - 1 \right] \times 1000$ (Coplen, 1994; Hoefs, 2009). Analytical error for the carbonate samples is $\pm 0.08\%_0$ for $\delta^{13}\text{C}$ and $\pm 0.10\%_0$ for $\delta^{18}\text{O}$. 
5 Exploring Environmental and Climatic Variation

In this chapter I address one of the main aims of this thesis – to categorise the underlying environmental variation in Early Medieval Europe and England. This is paramount for disentangling human action (migration or foodways) from underlying environmental variation. Furthermore, if we do not understand how England compares to its neighbours in terms of isotopic patterning how can we hope to identify movement and dietary differences between regions? Once this variation is better characterised, the larger scale questions of human action can be addressed in the following chapters.

This chapter is a systematic meta-analysis and as such I follow statistical procedures laid out in Chapter 3 to address the aim stated above. There are four elements (and their isotopes) and four tissues analysed in this chapter – carbon and nitrogen from human and faunal bone, and human dentine; and carbon, oxygen and strontium from human tooth enamel. Due to the different elements and tissues used, there are different kinds of underlying environmental variation to consider, as discussed in Chapter 2. Here I start with a sub-continental scale and then delve into variability within England. Faunal baseline data for diet are evaluated first, then I investigate human environmental variation. I compare patterns across geo-political regions, the effects of altitude, latitude and longitude on $\delta^{18}$O$_{\text{phosphate (SMOW)}}$ values, and the impacts of geology and environment type on human isotopic signatures.

I have subdivided western Europe into geo-cultural regions, as described in Chapter 3 (Figure 3-2). This was done based on known historical and archaeological data (material culture, political and linguistic boundaries, as best known) as well as the strontium and oxygen isoscape base maps for Europe (see Figure 5-11 and Figure 5-12). These allow me to look at localised isotopic patterning in each of the elements analysed. They are visualised as ridge and violin plots to highlight the distributions’ shapes, quartiles and outliers. These regional patterns are useful for disentangling environmental variation and isotopic patterning from human actions.

As mentioned in Chapter 3 there are differences in the methods and reporting of $\delta^{18}$O values. I converted all $\delta^{18}$O$_{\text{carbonate}}$ values to $\delta^{18}$O$_{\text{phosphate (SMOW)}}$ via the Chenery et al.
(2012) equation for ease of comparison between studies and the BGS maps for Britain. From here on the values are therefore referred to as $\delta^{18}O_{\text{phosphate}}$ or simply $\delta^{18}O$.

This meta-analysis highlights not only regional trends but also sampling biases (i.e. sampling mainly assumed migrants) and regions where more isotopic work for the Early Medieval period would be useful. Despite this there are some interesting interregional comparisons to be made. Ultimately these comparisons facilitate a better contextualised understanding of the data from England in terms of environmental variation, migration, culturally mediated fractionation and foodways. The aim here, as set out in Chapter 1, is to categorise and better understand any underlying environmental variation before tackling archaeological questions of mobility and consumption.

5.1 Faunal baselines and diet

As described in Chapter 2, faunal baselines are often used in archaeological (S)IAs for a better understanding of local isoscapes and food webs, and therefore aid the interpretation of human values. It is important to grasp the trophic relationships and associated $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$ values of the food sources so as to better explain any extreme or unexpected values in our human consumers. Rarely in our period is the associated settlement for any given cemetery known, let alone excavated, meaning there are large gaps in our knowledge of zooarchaeology in many locales. Due to the often-small sample sizes for sites or regions, the faunal data here are explored cautiously.

Ideally a variety of contemporary plant materials would also be included for baselines at the bottom of the food chain, however at time of writing, only one very recent paper has been published with Early Medieval English plant stable isotope ratios (Hamerow et al., 2020). The sample sizes are extremely small and multiple grains combined to produce each data point which potentially swamps a lot of the variation within the plant (Hamerow et al., 2020; Lightfoot et al., 2020). Whilst Hamerow and colleagues suggest that the changes they see may be reflective of wider English agricultural practices, this paper remains a one town case study and lacks data for the
entirety of our period and will therefore only be discussed more generally in later chapters.

5.1.1 Western Europe
The complete European faunal dataset can be seen as a scatterplot in Figure 5-1 (below) and can be compared to the English dataset by itself in Figure 5-2. There are 1799 faunal $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ bone entries from a variety of species. England dominates the dataset (n=992 over 55%, see Table 5-1 for regional totals), although most species have similar values between England and the continent. All animals occupy the expected isotopic niches, with the exception of some C$_4$ input herbivores (mentioned below).

<table>
<thead>
<tr>
<th>Region</th>
<th>Faunal sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Atlantic</td>
<td>41</td>
</tr>
<tr>
<td>Atlantic &amp; Arctic Norway</td>
<td>20</td>
</tr>
<tr>
<td>Skaggerak-Kattegat-Jutland Basin</td>
<td>102</td>
</tr>
<tr>
<td>Baltic</td>
<td>10</td>
</tr>
<tr>
<td>Scotland and Scottish Isles</td>
<td>210</td>
</tr>
<tr>
<td>Irish Sea</td>
<td>85</td>
</tr>
<tr>
<td>England</td>
<td>992</td>
</tr>
<tr>
<td>Frisia &amp; Saxony</td>
<td>69</td>
</tr>
<tr>
<td>Austrasia &amp; Burgundy</td>
<td>22</td>
</tr>
<tr>
<td>Austro-Hungary &amp; Bavaria</td>
<td>47</td>
</tr>
<tr>
<td>Croatia</td>
<td>17</td>
</tr>
<tr>
<td>Balearic &amp; Tyrrenian Seas</td>
<td>109</td>
</tr>
<tr>
<td>Inland &amp; Western Iberia</td>
<td>71</td>
</tr>
<tr>
<td>Unknown (Scandinavia)</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 5-1: Regional sample sizes for faunal carbon and nitrogen stable isotope data.

There are two major differences between the England and the whole European dataset; first are some marine fish with $\delta^{15}N_{coll}$ values between approximately 7 and 11‰, and $\delta^{13}C_{coll}$ values upwards of -17‰. These fish are largely from “Viking” layers in Aarhus and are from a variety of species – mullet, cod, flounders, garfish, greater weever, herring and salmonids. These values are typical of marine fish from the Baltic (Barrett et al., 2011; Hutchinson et al., 2015; Orton et al., 2011). There are
also some Mediterranean sites with marine fish in this range – shark, dory, mullet and tuna mostly from Iberian sites (Alexander et al., 2019; López-Costas and Müldner, 2016; Swenson, 2019). The comparatively smaller number of marine fish from English contexts within this range are all from Anglo-Scandinavian contexts in York which is interesting to consider given the Aarhus material (Müldner, 2005; Müldner and Richards, 2007). The second group of fauna with a clear difference in Europe compared to England are some herbivores with potential C₄ input, with δ¹³Ccoll values above -19‰. These are from a variety of species – ovicaprids, horses and cattle from sites along the Mediterranean and across the Iberian peninsula – A Lanzada (Spain), Almoina 8 &10 Valencia (Spain), Monte da Cegonha (Portugal), Missingac (France) & Nuštar (Croatia) (Alexander et al., 2019; López-Costas and Müldner, 2016; Mion et al., 2019; Saragoça et al., 2016; Vidal-Ronchas et al., 2019).

Freshwater and “other” fish as a group have the broadest range in δ¹³Ccoll values from -27.3 to -9.3‰ which reinforces the complexity of carbon isotope routing in these ecosystems mentioned in chapter 2. Birds, both domestic and wild taxa, also have broad ranging δ¹³C and δ¹⁵N values. This reflects the variety of feeding behaviours in wild birds but also the tendency of domestic fowl to occupy higher trophic levels similar to omnivorous and carnivorous species.

Herbivorous species are very homogenous with the exception of those with some potential C₄ input (mentioned above) and some ovicaprids whose δ¹³C and δ¹⁵N values are more similar to fowl and omnivores which could be indicative of seaweed foddering or other sea-spray effects, or caprine omnivory (Schulting et al., 2017). Carnivorous species such as cats and dogs have stable isotope ratios reflective of high animal protein diets, higher than the majority of herbivores, with some individuals showing potential C₄ or marine input (either direct or through the food chain). Marine species, both mammals (cetaceans and pinnipeds) and fish (with two suspected salmonid exceptions plotting with freshwater species to the left of Figure 5-1) show the impact of longer marine food chains nicely, with δ¹³C values above -18.5‰ and δ¹⁵N values all above 7.0‰.

Many human stable isotope studies do not include faunal data leaving large gaps in certain regions. This, combined with the regionally different sampling of species for
IA, is an interesting conundrum, especially if we wish to consider using SIMMs for human diets. As the focus tends to be on herbivore species to get an easy trophic-level offset estimate, some studies do not include the whole breadth of animals which may have formed part of the human diet and which provide vital information if we want to attempt such models. As already stated, this is for a variety of reasons, often outside the control of the researcher, but it is why ultimately, in the case study chapter, SIMMs proved problematic and were not attempted.
Figure 5.1: Scatterplot of Early Medieval European faunal $\delta^{13}C$ and $\delta^{15}N$ values, colours and symbols vary by Species Group.
Figure 5-2: Scatterplot of Early Medieval English faunal $\delta^{13}$C and $\delta^{15}$N values, colours and symbols vary by Species Group.
5.1.2 England

The faunal data from England can be seen above in Figure 5-2. Whilst England dominates the faunal dataset, there are some notable differences between Figure 5-1 and Figure 5-2 which were described above. Another gap in the English dataset is marine mammals, which are found in Early Medieval contexts but only those at Flixborough have been subject to stable isotope analyses. However the raw data were not reported (only the means), so I was unable to include them in this study (Dobney, 2007: 199–203; Gardiner, 1997; Gardiner et al., 1999). The focus of faunal sampling on herbivores is apparent, with the input from the Medieval fish project (both control and target samples included see Digital Appendix) by Barrett et al. (2011) sorely needed. However other species also need this kind of focussed attention, especially freshwater fish and a variety of wild species. This is necessary for a better understanding of the impacts of Early Medieval agriculture on all aspects of the food chain, and any freshwater portion of the diet especially considering early Christian fasting practices which required abstention from eating land mammals (Banham, 2004: 63–70; Hagen, 2006: 393–408; Reynolds, 2015; Serjeantson and Woolgar, 2006). There are often assumptions made about the fauna in elite versus rural settlements and the role of animals in Early Medieval contexts, depending on the kind of site (e.g. lots of pigs in Kentish elite sites, which changes to lots of chicken and fish when they become monasteries, versus more ovicaprids in small rural settlements) (Dobney, 2007; Holmes, 2016; Knapp, 2018). Knapp (2018, 298-301) sees this as seriously limiting the broader impact and understanding of human-animal relationships, farming and foodways in our period.

Not only are there species biases in the dataset but there are also regional differences in sampling within England (e.g. Table 5-2). These can be explained by certain sites (like York) having particularly robust zooarchaeology and resources to construct baselines or particular research group interests and other doctoral studies focussing on areas such as Wessex and the East (Hull, 2007; Müldner, 2005; Müldner and Richards, 2007). Therefore, there is still a lot of ground to be covered in the future to better understand Early Medieval isotopic ecology in England across a range of fauna and regions.
Figures 5-3 to 5-6 detail the character of the regional $\delta^{13}C$ and $\delta^{15}N$ herbivore data in England. These herbivore plots include both domestic and wild taxa, excluding small mammals. These figures show clearly the impact of different research agendas and also the survival of and ease of access to faunal material in different regions. Many of the differences between regions in terms of ranges, means and medians, quartiles and shape of distributions can be explained by sample sizes and presence/absence of wild taxa. A summary of faunal counts and presence/absence of wild herbivores, fish and birds can be found in Table 5-2. For $\delta^{13}C$ values (Figure 5-3 and Figure 5-4) the central tendency for all regions is between -23 and -21‰, with the East being noticeably skewed left, and there being some degree of multimodality in all regions. For $\delta^{15}N$ values (Figure 5-5 and Figure 5-6) ranges are similar across regions; however differences in centrality and modality are far more marked.

![Figure 5-3: Ridge plot of Early Medieval herbivore $\delta^{13}C_{coll}$ values in England by region.](image1)

![Figure 5-4: Violin plot of Early Medieval herbivore $\delta^{13}C_{coll}$ values in England by region.](image2)
The similarity in $\delta^{13}C$ values across regions are a reflection of the $C_3$ terrestrial plant species in England with no indication of any $C_4$/marine foddering of cattle or ovicaprids. The differences in $\delta^{15}N$ values across herbivorous species are less straightforward. There is bimodality in Kent and East Sussex, a tail of higher $\delta^{15}N$ values in Yorkshire and North Lincolnshire, multimodality in most other regions and Wessex’s peak is lower than the other regions.

**Figure 5-5:** Ridge plot of Early Medieval herbivore $\delta^{15}N_{coll}$ values in England by region.

**Figure 5-6:** Violin plot of Early Medieval herbivore $\delta^{15}N_{coll}$ values in England by region.
The canonical value for trophic enrichment of $\delta^{15}$N values is $3\%_o$ with constrained predator-prey studies suggesting values of between 2.4-4.8$\%_o$ between prey and predator collagen. Given that some regional herbivore $\delta^{15}$N ranges are above $5\%_o$, these animals appear isotopically to occupy different trophic levels and a variety isotopic niches which are unexpected of terrestrial $C_3$ herbivores (Bocherens and Drucker, 2003).

There is yet to be a fully systematic work published on isotopic variation of different domestic species for Britain that would allow us to better quantify offsets between species in the same geographical context, as was recommended by Hedges and Reynard (2007) amongst others. Similarly variation within a species also is cause for concern, and is not a problem just found here; when interrogated, the data show that the individual animals with the highest and lowest $\delta^{15}$N values in any region are not systematically from a particular species, so it cannot be purely physiological differences driving this variability and broad range in values. There are a greater number of ovicaprids with $\delta^{15}$N values above $7.0\%_o$, perhaps suggesting at least some of these animals were goats and therefore possibly omnivorous rather than herbivorous. However, there are sheep, cattle and horses with high $\delta^{15}$N values compared to others of their species in the same region or site.

There are several possible explanations for this. As information about age at death/slaughter was not widely available for the majority of the faunal data, it is possible some of these animals could be juveniles and therefore show a nursing effect in their $\delta^{15}$N values. Alternatively, since it is widely assumed that herbivore values reflect local vegetation through “bio-sampling”, these difference may in fact reflect differences in herd management/graazing and varying agricultural practices either chronologically or spatially (Hedges and Reynard, 2007). Some possible causes for shifts in plant $\delta^{15}$N values (but not $\delta^{13}$C) which would be reflected in these herbivores are changes in soil nitrogen such as manuring or water availability. Depending on which plant tissue the animals are eating, these increases in $\delta^{15}$N could be even more pronounced. There is also a link between warmer climates and soil nitrogen loss which in turn causes increases in $\delta^{15}$N values through the food chain, meaning that we could perhaps see chronological changes due to the MWP (Ambrose, 1991; Bogaard et al., 2007; Commissio and Nelson, 2007; Hedges and Reynard, 2007;
Lightfoot et al., 2020). If these animals are indeed reflecting differences in local plant signatures, for whichever reason, this could be very interesting not only for studying Early Medieval farming practices but also for studying climate change and the interpretation of high $\delta^{15}$N values in humans.

There is evidence in the zooarchaeological literature that there are changes not only in the size and management of domestic herbivore species during the Early Medieval period, but also changes in the relative proportions of different species being consumed (Crabtree, 1989, 1996, 2012; Rizzetto et al., 2017). For instance in Knapp's (2018) study of the elite site Lyminge in Kent, there are changes in red meat feasting patterns as well as increasing numbers of fish and fowl at the site, consistent with the introduction of Christianity to the region, construction of a church at the site and its eventual evolution from elite hall complex to monastic compound. Hence the

<table>
<thead>
<tr>
<th>Region</th>
<th>Total Faunal Sample</th>
<th>Herbivore Sample</th>
<th>Wild herbivore taxa?</th>
<th>Fish?</th>
<th>Birds?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast York and North Lincolnshire</td>
<td>17 10</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Central</td>
<td>11 9</td>
<td>Yes (1 roe deer)</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>East</td>
<td>263 170</td>
<td>Yes (2 deer)</td>
<td>Yes (1 freshwater, 17 marine, 2 other)</td>
<td>Yes (10 domestic, 5 other)</td>
<td>Yes (1 domestic)</td>
</tr>
<tr>
<td>Upper Thames and Chilterns</td>
<td>91 72</td>
<td>No</td>
<td>No</td>
<td>Yes (1 domestic)</td>
<td>No</td>
</tr>
<tr>
<td>London</td>
<td>45 0</td>
<td>No</td>
<td>Yes – exclusively (45 marine)</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Wessex</td>
<td>192 160</td>
<td>No</td>
<td>Yes (8 marine)</td>
<td>Yes (6 domestic)</td>
<td></td>
</tr>
<tr>
<td>East Sussex and Kent</td>
<td>144 63</td>
<td>Yes (1 roe deer)</td>
<td>No</td>
<td>Yes (44 domestic)</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-2: Summary table for regions in Early Medieval England with carbon and nitrogen stable isotope data, overall counts, herbivore numbers and presence/absence of certain taxa in isotopic datasets.
inclusion of presence/absence data for these fauna in Table 5-2. Whilst the presence or absence of fish and birds in isotopic studies is not proof in and of itself that certain regions see similar patterns to those at Lyminge, they at least show where these patterns might be present, and regions where more work could be conducted. Fish are not only linked to Christian religious food laws. For sites within the Danelaw and during the reign of Cnut in England, increases in fish bones and marine consumption have been used as evidence for the “Fish Event Horizon” and Scandinavian settlers, although often finding these settlers has proved difficult but not impossible using isotopic data (Buckberry et al., 2014; Müldner, 2005, 2016; Müldner and Richards, 2007; Pollard et al., 2012). This claim of increasing fish remains and consumption as a the result of Scandinavian influence was originally for the Scottish isles (Hiberno-Norse communities), and holds well there; for England Barrett and colleagues see a growing demand for marine fish, which may be driven by increasing urbanism as well as Scandinavian links in the lead up to and after 1000 AD (Barrett et al., 2004a; Barrett and Richards, 2004; Barrett, 2016; Orton et al., 2017; Buckberry et al., 2014). Contemporary fish bone isotopic data alongside human data can help investigate these claims of different cultural influences, as I do below.

Whilst this section is not a comprehensive survey of all Early Medieval zooarchaeology in England (that is far beyond the scope of this thesis), it collates for the first time the bulk of faunal stable isotopes for the period so as to better interrogate the data in terms of environmental variation across the food chain and better assess human foodways.

5.2 Human isotopic variation – western Europe

This section continues to address the research aim of categorising and confirming underlying environmental variation, here on human tissues – enamel, bone and dentine. This is done by first comparing regional signatures across western Europe and then by assessing the effects of climate, geology and environment type. This section addresses the data on a sub-continental scale across Europe, with section 5.3 doing the same within England.

There are 1833 human enamel entries in my database when bone apatite is excluded.
This covers 14 regions, 20 modern countries, and 200 sites. The human bone collagen dataset is by far the largest of those analysed in this thesis (assembly detailed in Chapter 3). There are 4149 individual entries from 194 sites across 16 geographic regions (21 modern countries). The human dentine collagen dataset is considerably smaller than bone, with 931 entries, across 58 sites, seven modern countries and seven regions, with 614 bulk samples and 317 incremental samples.

Figure 5-7 and Figure 5-8 show the western European and English data for the pairs of tooth enamel isotopic data with marginal scatterplots to highlight outliers, means and quartile ranges of the data. Both figures showcase the wide range of δ¹⁸O values found across Europe (12.8-20.8‰, mean = 17.2‰) with outliers at each end.

Strontium (see Figure 5-7) has a tight range when outliers are excluded (0.7063-0.7422) with the mean (0.7121) reflecting the majority of individuals coming from younger non-volcanic geologies. The long tail of increasing ⁸⁷/⁸⁶Sr values reflects the less common outcrops of geologies in Europe which can produce such values in mammalian tooth enamel (see Figure 5-11 for examples in orange-red). δ¹³C values in Europe have a similarly long tail of outliers (Figure 5-8), like ⁸⁷/⁸⁶Sr, but with a bigger range (-16.9 - -4.7‰, mean= -13.7‰). The majority of δ¹³C values lie within the C₃ range for enamel and the outliers lying in the C₄/marine zone (Kusaka et al., 2015; Lee-Thorp et al., 1989; Loftus and Sealy, 2012).
Figure 5-7: Scatterplot of Early Medieval human tooth enamel with paired $\delta^{18}O$ and $^{87}\text{Sr}/^{86}\text{Sr}$. Orange = individuals buried in England, black = all other European individuals.

Figure 5-8: Scatterplot of Early Medieval human tooth enamel with paired $\delta^{13}O$ and $\delta^{13}C$. Orange points = individuals buried in England, black = all other European individuals.

In Figure 5-9 below, paired bone $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}_{\text{coll}}$ values are shown in a scatterplot with marginal box plots to highlight outliers and the interquartile ranges of the data. It shows that in the larger European dataset there are outliers at both the upper and lower ends of the $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}_{\text{coll}}$ ranges (-24.1 to -12.8‰ and 0.0 to 19.1‰)
Ranges of over 10% for both $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}_{\text{coll}}$ suggest that Early Medieval humans were occupying several different isotopic niches with large variations in animal protein consumed. The majority of $\delta^{13}\text{C}_{\text{coll}}$ values lie within the $\text{C}_3$ range for bone collagen, and the outliers lie in the $\text{C}_4$/marine zone, similar to that which was seen for $\delta^{13}\text{C}_{\text{enamel}}$ enamel values above (Kusaka et al., 2015; Lee-Thorp et al., 1989; Loftus and Sealy, 2012; Schoeninger and DeNiro, 1984). The lower $\delta^{13}\text{C}_{\text{coll}}$ values are consistent with freshwater fish and aquatic bird species above in Figure 5-1 and Figure 5-2, perhaps indicating diets richer in freshwater resources. For high $\delta^{15}\text{N}$ values this suggests a higher trophic level either through aquatic (freshwater and/or marine) resource consumption, a greater proportion of omnivore protein in the diet and/or increased terrestrial protein consumption, but, as we have seen above with the faunal data, this could be complicated by herbivores (and omnivores for that matter) who have “bio-sampled” higher $\delta^{15}\text{N}$ plants. Individuals who are outliers with low $\delta^{15}\text{N}$ values despite passing collagen preservation screening procedures may still be the result of diagenetic processes or represent diets with little to no animal protein (O’Connell and Hedges, 1999; O’Connell et al., 2012; Hedges and Reynard, 2007).

*Figure 5-9: Scatterplot of Early Medieval human bone collagen with paired $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values. Orange= individuals buried in England, black = all other European individuals.*
I included both incremental and bulk dentine samples in the database but Figure 5-10 only includes bulk samples or averaged incremental results as proxies for bulk samples. As with the other tissues and isotope combinations above, the majority of dentine $\delta^{13}$C_{coll} and $\delta^{15}$N_{coll} data are from England (68%), with Croatia, the Po Valley, Scotland and the Scottish Isles, the Baltic, Skagerrak-Kattegat-Jutland Basin and Atlantic and Arctic Norway also represented. The western European dentine dataset has similar outliers and a long, less negative, tail in $\delta^{13}$C_{coll} values compared to those seen for bone and enamel above. $\delta^{13}$C_{dentine} has a range of 7.9‰ and a mean of -19.6‰ in western Europe. Dentine $\delta^{15}$N_{coll} is more uniform in its distribution with no statistical outliers; the range is 11.2‰ with a mean of 11.9‰. The ranges for both $\delta^{13}$C and $\delta^{15}$N, as with bone, show the diversity in resource consumption across Early Medieval Europe and individuals spanning several trophic levels. It is clear from the forked appearance of the data in Figure 5-10 and the long tail of $\delta^{13}$C values that there are people with $C_4$, marine and a variety of terrestrial childhood diets in these populations.
Figure 5-11: Random forest regression of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ mapped for Western Europe from Bataille et al. (2018) licensed under CC-BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Figure 5-12: Modelled $\delta^{18}O$ annual precipitation map for Europe (G Bowen, 2019). Reproduced with permission from G. Bowen.
5.2.1 Regional variation
This section focuses on taking the broader western European trends seen above and comparing them across geo-political zones to better contextualize England and establish regional variation. Understanding how regions differ in their isotopic signatures forms the basis for teasing apart environment and culture over the coming chapters.

5.2.1.1 Regional climate and δ\textsuperscript{18}O values
Beginning with δ\textsuperscript{18}O values (Figure 5-13 and Figure 5-14), there is a large degree of variation between and within regions in terms of their summary statistics and distribution shapes. Generally, in the ridge plots the longer and less bell curve-like the distribution, the larger the sample size and wider the range. Figure 5-14 demonstrates how several regions (e.g. Croatia and England) have individuals which span most of the pan-European range (over 8‰). Such ranges are larger than we would expect within a population, as baselines (e.g. Figure 5-12) show precipitation ranges of 2-4‰. Recent studies suggest archaeological populations are likely to have ranges above 3‰ due to physiological factors, use of multiple-water sources and human modification of drinking water (G Bowen, 2019; Evans et al., 2012; J Evans et al., 2018; Lightfoot and O’Connell, 2016). As discussed in Chapter 2, there are many environmental factors which could alter the δ\textsuperscript{18}O values of drinking water sources and individuals from baselines (e.g. seasonality, deep well water, snow melt); however the large ranges we see in Figure 5-13 still seem highly implausible if a largely local population with a range of 3-4‰ is assumed. Therefore, other explanations such as migration, water transportation (e.g. aqueducts) or a high degree of “brewing and stewing” must be considered and will be explored later in this thesis.
Figure 5-13: Ridge plot of Early Medieval European tooth enamel $\delta^{18}$O phosphate values by region, coloured by quartile.

Figure 5-14: Violin plot of Early Medieval European tooth enamel $\delta^{18}$O phosphate values by region.

For Inland and Western Iberia, the pattern is much as expected (~17.5-21‰) given the variety seen between the Atlantic coast and higher altitude areas on Figure 5-12. Not much can be said about the Balearic and Tyrrenhian Seas given $n=6$, however the spread and interquartile range is still bigger than the 2‰ drinking water range of the island locale of these burials, and a mixture of local, Andalusian or other non-local origins were proposed by the original researchers (Dury et al., 2019). Croatia is one of the few non-Anglo-Scandinavian regions with a good sample size for $\delta^{18}$O analyses ($n=326$), so it is unlikely that the spread in values seen here is purely an artefact of sampling. Whilst there are significant differences in MAP values between coastal and inland sites in Croatia, some values still do not fit for the region. Both migration and
aqueducts carrying $^{18}O$ enriched water from the mountains have been proposed, and, given some individuals’ $\delta^{13}C_{\text{Carb}}$ values, migration seems very likely for those with lower $\delta^{18}O$ values (Lightfoot et al., 2014; Vidal-Ronchas et al., 2019). The signature in the Po Valley reflects its proximity to the Alps and connections into the Adriatic. Here, too, migrants have been proposed, with similar $C_4$ consumption to the Croatian sites (Amorim et al., 2018; Iacumin et al., 2014).

The Frankish areas of Austrasia and Burgundy, Normandy/Neustria, and Frisia and Saxony are more constrained in their ranges (overall and interquartile) and the $\delta^{18}O$ values align well with Figure 5-12, although the relatively small sample sizes in these areas must be considered (n= 63, 11, and 21 respectively). Individuals buried in the Irish Sea zone are interesting as very few reflect the $\delta^{18}O_{\text{MAP}}$ range of -9.4 to -5.5‰ from Bowen (2019). The original researchers for these sites credit migrants from either Scandinavia (Vikings) or the Mediterranean for the individuals at both extremes of the region’s range. The underlying assumptions of these claims will be tested below (Evans et al., 2012; Freke, 2002; Hemer et al., 2013, 2014; Knudson et al., 2012; Montgomery et al., 2014; Symonds et al., 2014; Wilson and Standish, 2016). Mainland Scotland and the Scottish Isles also suffer from small sample sizes (predominantly due to preservation problems in unfavourable soils) and sampling biases towards Norse-style burials. Therefore, the data from Scotland should also be interpreted with caution as it may not represent the natural isotopic variability in the region.

All three Fennoscandian regions (the Baltic, Skagerrak-Kattegat-Jutland Basin and Atlantic and Arctic Norway) have good sample sizes (n=70+), similarly large ranges (approximately 13-21‰) and means (16.6‰, 16.6‰, 17.1‰), but with different distribution patterns. Whilst a large range of meteoric water values is possible across Fennoscandia, the highest values in humans are not consistent with known sources of natural drinking water in these regions. Due to the geographical and climatic differences between the Baltic, Jutland and its surrounds and the Atlantic coast of Norway we would not expect to see such similarities between these regions in oxygen (or strontium, see below) isotope values unless there was a high degree of mobility throughout the Baltic and Fennoscandian zone. The Skagerrak-Kattegat-Jutland Basin should theoretically have very homogenous $\delta^{18}O$ values, according to Figure 5-12.
However, what we see is a mixture of signals which are more consistent with origins closer to the Arctic Circle, as well as southerly parts of Europe. This similarity in $\delta^{18}O$ variability across the Fennoscandian regions supports historical narratives and previous research on human mobility in the area, showing how wide-spread and consistent human mobility was, stretching from the Arctic to the Mediterranean and perhaps beyond. The seventeen North Atlantic individuals from Thjodhilde’s Church Greenland are all assumed to be Norse migrants from Scandinavia (southern Norway and Denmark, and possibly also Iceland) which the available data supports (Fricke et al., 1995). The other seven North Atlantic individuals from Mosfell in Iceland in the apatite database only have strontium and not oxygen data so could not be compared here (Grimes et al., 2014).

England has a distribution shape and quartiles that are very similar to Atlantic and Arctic Norway (Figure 5-13), and, like Croatia and the Fennoscandian regions, a range larger than its isotopic baselines (13.7-20.3‰). Evans et al. (2012) suggest a $\delta^{18}O_{phosphate}$ range for Britain as a whole of approximately 15-19.5‰ (mean = 17.7‰), having excluded many of the individuals in the database here, through (by their own admission) somewhat circular reasoning. Their updated biosphere map for Britain has tightened that range to 16.6-18.7‰ (J Evans et al., 2018). My comparative analysis suggests that this tightened range from Evans et al. (2018), especially for England by itself, is more reflective of local individuals and drinking water values than earlier estimates, and this therefore suggests that many burials in the England dataset are non-locals (see sections 5.3.1 and 6.1.2). This does not, however, account for “brewing and stewing” which is considered separately below in section 6.2.

5.2.1.2 Regional $^{87/86}\text{Sr}$ values and geological variation

The human $^{87/86}\text{Sr}$ ranges, like those of $\delta^{18}O$, are surprising because, in many regions, they extend far beyond their expected values given by bioavailable strontium maps and underlying geologies. This adds weight to the prevailing archaeo-historical narratives of high levels of migration during this period. The majority of European regions included here have extremely similar $^{87/86}\text{Sr}$ distributions and means (Figure 5-7 and Figure 5-15) which are relatively constrained between approximately 0.706-0.713, with long tails of more positive values in all bar the North Atlantic (Figure
This shows that the tail in Figure 5-7 is not just an artefact of one region. The Fennoscandian regions stand out in the shape of their distributions (especially the Baltic) which are more positively skewed. The Jutland peninsula for instance is mostly Cenozoic sediments with lower bioavailable strontium ranges (approx. 0.70701-0.71100, similar to England), but it produces many burials with higher values in their tooth enamel. There is a large amount of natural geological variation which is expounded by a high degree of regional mobility in Scandinavia and the Baltic which is responsible for these patterns. Another factor contributing to these patterns could be marine fish consumption; however, feeding experiments are inconclusive on exactly how marine resource consumption impacts dental tissue $^{87/86}$Sr values (but effects are seen in [Sr]), although if dietary input was high and terrestrial diets were sourced from geologies sufficiently different in $^{87/86}$Sr from seawater (i.e. not young calcareous geologies) values may be drawn closer to seawater $^{87/86}$Sr values (approx. 0.7091 although this varies globally and chronologically) (Lewis et al., 2017; Spooner, 1976).

Figure 5-15: Ridge plot of Early Medieval European tooth enamel $^{87/86}$Sr values by region, coloured by quartile.
The Fennoscandian Shield is not the only geological area which can produce high strontium isotope ratios (but it does produce some of the highest, given current data). There are other regions of uplift and deep-time volcanic activity which have sampled or predicted \(^{87}/^{86}\)Sr values of up to 0.7300. These include the Scottish Highlands and Outer Hebrides, Northern Ireland and the most westerly tips of Co. Mayo and Galway, parts of Wales and Cornwall, the Armorican Massif (Normandy and Brittany), the Central Massif (southwest France), the Pyrenees, Cantabrian Mountains, the Iberian Massif and Baetic System, the Alps and the Bohemian Massif, with Corsica and Sardinia also possibly giving high values (Bataille et al., 2018; Voerkelius et al., 2010; Willmes et al., 2018). These geological formations give such high strontium ratios because they are dominated by Precambrian and Lower Palaeozoic metamorphic rocks. Any tooth enamel values over 0.73 are likely to be migrants from the Fennoscandian Shield, although origins from other European massif systems could also be possible, given predicted values from agricultural and geological studies (Bataille et al., 2018; Voerkelius et al., 2010; Willmes et al., 2018). More geological, plant and water samples are needed to confirm this.

Interestingly, the lower values in the North Atlantic (Iceland) are not what we would expect given the traditional Landnám stories of settlers from Norway who would presumably have much higher values given the graphs above (Figure 5-16 does show a few individuals with more radiogenic signals) (Grønlie, 2006; Porgilsson, 1972). With n=7 from one small settlement it is hard to extrapolate for all of Iceland, but this

Figure 5-16: Violin plot of Early Medieval European tooth enamel \(^{87}/^{86}\)Sr values by region.
could be explained by a few different scenarios. Firstly, as Iceland’s geology is mostly formed by (geologically) recent volcanic activity and thus gives lower $^{87/86}\text{Sr}$ values, some of these individuals could be second generation settlers, but this is less likely given radiocarbon dates and archaeological evidence at the site (Grimes et al., 2014). Secondly, given the very diverse pattern of $^{87/86}\text{Sr}$ values in the Scandinavian homelands, it is very possible that some of these settlers may not have been born in Norway, but in other parts of Scandinavia which were under the control of Norway at the time. Following on from this, recent genetic evidence from Iceland also shows that there were significant British and Irish genetic inputs into the founding population and so the smaller $^{87/86}\text{Sr}$ values could be from these regions (and conversely some of the higher $^{87/86}\text{Sr}$ values could be Hiberno-Norse and not Scandinavian in origin) (Ebenesersdóttir et al., 2018). With more data these theories could be tested.

Many of the higher enamel $^{87/86}\text{Sr}$ values in other European regions, can also be explained by migration from one of these older geological regions, and archaeological and/or genetic evidence (where available) can help lend weight to which region, alongside the use of other stable isotopes. For instance the Norse grave goods with individuals in Scotland and its islands support assumptions of Scandinavian origin when matching $\delta^{18}\text{O}$ and $^{87/86}\text{Sr}$ values could in some cases be found in regions closer to the burial site (Evans et al., 2012; Harris et al., 2017; Montgomery et al., 2003, 2014).

Given these regional patterns and metamorphic geologies influencing $^{87}\text{Sr}/^{86}\text{Sr}$ values across Europe the implications for mobility in England are complex. The comparisons in Figure 5-15 and Figure 5-16 highlight the difficulties in using $^{87}\text{Sr}/^{86}\text{Sr}$ values to provenance individuals with any great specificity. That said, what has been demonstrated is that many of the values from individuals buried in England are not possible from English geologies, let alone those on which they are buried, so there was a high degree of migration and mobility into Early Medieval England from a range of possible locations. In Figure 5-16 England’s $^{87/86}\text{Sr}$ values look very similar to the Fennoscandian regions, although with a more skewed towards lower values (Figure 5-15). Since values above 0.713 are not possible from English geologies, with other British and Irish geologies capped at 0.7221 (given current data), and these lower values are very similar for much of Europe, a significant number of individuals
must therefore originate from Fennoscandia or Massif-like geologies. Due to the similarities between much of western Europe’s geologies and bioavailable strontium values (and climates as shown above) there are likely far more migrants which are not visible isotopically.

Regardless of exactly where these high strontium isotope values could originate from, these left skewed distributions with long tails to the right give tantalising evidence of large scale Early Medieval European mobility. Some regions are distinctive in all three isotopes which is encouraging for provenancing applications and suggests that combining indicators of climate ($\delta^{18}$O), environment ($\delta^{13}$C) and geology ($^{87}/^{86}$Sr) is a powerful tool for human palaeoecology more broadly. Since my main focus is on using these meta-analyses to contextualise Early Medieval England this high degree of variability and potential power of combining $\delta^{18}$O, $\delta^{13}$C and $^{87}/^{86}$Sr will be utilised for UML interpretation in Chapter 6 and 7.

5.2.1.3 Regional human diet

5.2.1.3.1 Enamel $\delta^{13}$C_{carb}

It is important to note here (and will be discussed further below with dentine in section 5.2.1.3.3) that as mentioned in Chapter 2 different teeth have different formation timings, and that enamel and dentine from the same tooth also represent different formation times as well as different dietary routing. Whilst I aimed to analyse PM2s and M2s for my own laboratory work, the data available from the literature is far broader in scope and represents dental formation from in utero/birth through to early adulthood due to differing research questions (e.g. breastfeeding/weaning studies). For enamel deciduous teeth make up ~2% of the data, and M1s (the earliest forming permanent teeth) account for ~11% (see Digital Appendix).

Enamel $\delta^{13}$C_{carb} values across Europe show a continuum between C4/marine based diets and a variety of C3 diets (freshwater and terrestrial) (Figure 5-17 and Figure 5-18). These values come from the bioapatite portion of the tooth enamel, usually using the Balasse method which measures $\delta^{18}$O in the carbonate ion of enamel
apatite. $\delta^{18}$O\textsubscript{carbonate} can be converted to $\delta^{18}$O\textsubscript{phosphate}, as was done here, but the Balasse method is less popular (see Chapters 2 and 3) (Balasse et al., 2002).

![Ridge plot of Early Medieval European tooth enamel $\delta^{13}$C\textsubscript{carb} values by region, coloured by quartile.](image)

![Violin plot of Early Medieval European tooth enamel $\delta^{13}$C\textsubscript{carb} values by region.](image)

Again, sample size differences are a confounding factor, with England dominating the dataset (n=254), the majority of which comes from my own laboratory work here (n=200). It is assumed here that values above -12‰ are indicative of a moderate to large C\textsubscript{4} and/or marine contribution to whole diet (Ambrose and Norr, 1993; Dury et al., 2019; Kellner and Schoeninger, 2007). In more easterly parts of Europe, around the Mediterranean, or with links across Eurasia or North Africa there is clear evidence for C\textsubscript{4} and/or marine diets in enamel carbonate, often more so than in bone collagen. Here this can be seen in the Balearic & Tyrrhenian Seas, Croatia and Po Valley regions, where C\textsubscript{4} crop consumption (rather than marine resources) is
presumed to be the main resource causing this shift to more positive $\delta^{13}C_{\text{carb}}$ values (Amorim et al., 2018; Dury et al., 2019; Iacumin et al., 2014; Vidal-Ronchas et al., 2019). Some marine dietary input cannot be completely excluded using enamel carbonate alone but will be considered in alongside collagen data in Chapter 7. However, regionally specific whole diets are useful for the identification of migrants in combination with other isotopes.

There are a fourteen individuals in Austrasia & Burgundy, England, the Baltic, the Skagerrak-Kattegat-Jutland Basin and Atlantic & Arctic Norway which have values close to or in excess of -12‰. Individuals in these regions with these kinds of values could be seen as the traditional marine fish consuming "Vikings"; however, if this was the case it is odd that they are outliers in the Fennoscandian regions, and that none of the Scandinavian settlers in the Irish Sea region display these $C_4$/marine $\delta^{13}C_{\text{carb}}$ values. In the Austrasia and Burgundy region, the Dirmstein cemetery is inland but on the Rhine. Here the original investigators suggested Scandinavian settlers, as it is highly improbable that local inhabitants had access to either $C_4$ crops or marine resources (Schuh and Makarewicz, 2016). Whether this is correct invariably lies with these individuals’ $\delta^{18}O$ and/or $^{87/86}Sr$ values and, where available, collagen analyses as well. For some of these outliers in northern regions, a Mediterranean origin seems more likely especially considering the cluster analysis below for all tissues (Chapters 6 and 7). The implications for this and the FEH will be discussed in later chapters, especially in terms of England and apatite-collagen spacing seen there.

The lack of clear marine consumption in enamel $\delta^{13}C_{\text{carb}}$ values in Fennoscandia is perplexing given the regions’ bone and dentine values below, which indicate significant marine protein consumption, especially in Norway. Human $\delta^{13}C_{\text{carb}}$ values and their reflection of whole diet are physiologically and metabolically complex and still relatively poorly understood compared to collagen as discussed in Chapter 2. When considering this mismatch between tissues, and the implications for tissue offsets (which will be analysed in more detail for England in Chapter 7), there are several factors in whole diet (which apatite reflects versus the protein portion of diet in collagen) which may result in these comparatively negative $\delta^{13}C_{\text{carb}}$ values. Firstly, the data for enamel, dentine and bone are not representative of the exact same individuals, despite some overlap in who has been sampled (issues with survivorship
and matched tissues are discussed in more detail below and in Chapter 7 for England), so the enamel values here might not in every case be the marine resource consumers represented by dentine and bone collagen below. Secondly, lipids and carbohydrates with more negative $\delta^{13}C$ values could be “swamping” the marine protein values in the enamel; lipids are generally more depleted in $^{13}C$ than whole muscle, so significant fish consumption (of any kind) which are high in fats may pull enamel values towards more terrestrial values. However, known values for European fish (freshwater, brackish and marine) suggest that lipids, whilst $^{13}C$ depleted compared with whole tissue, would not alter consumer tissues towards more terrestrial values, but that in fact larger sources of variation in fish tissues come from different species physiologies and the environment type primarily (Apolinarska et al., 2016; Kiljunen et al., 2006; Newsome et al., 2014; Sisma-Ventura et al., 2019; Webb et al., 2017). For instance, salinity and temperature can have really strong impacts on the same species, giving some basis for identification of fisheries/catchment areas (Apolinarska et al., 2016; Barrett et al., 2011; Budge et al., 2016; Dempson et al., 2010; Grupe et al., 2009; Guiry, 2019; Häberle et al., 2016; Kiljunen et al., 2006; MacKenzie et al., 2012; Orton et al., 2011; Robson et al., 2016; Sisma-Ventura et al., 2019).

Perhaps the best comparison in archaeological human data is from Jomon era populations in Japan (Kusaka, 2019; Kusaka et al., 2015). These studies demonstrate the importance of nutritional/metabolic balance and macronutrient pools in interpreting enamel carbonate values and apatite-collagen offsets. Despite marine signals in collagen isotopic values, these individuals had bioapatite values and tissue offsets similar to those seen here for Norway; Kusaka (2019) interprets these as marine resources dominating the protein portion of the diet, but other terrestrial resources contributing more to whole diet and energy sources, and hence more terrestrial $\delta^{13}C$ values are reflected in their bioapatite. This model would suggest less of a juxtaposition between fish remains in the archaeological record, marine protein consumption signatures in collagen IA and $\delta^{13}C_{\text{carb}}$ values, but instead the complexity of human dietary routing. It appears that marine signatures may not isotopically dominate all tissues and macronutrient pools in the body when consumed. Therefore, in Fennoscandian regions where the majority of dietary protein appears to be from
marine resources (see below), the larger balance of whole diet seems to be terrestrial based given their enamel $\delta^{13}C_{\text{carb}}$ values.

The majority of $\delta^{13}C_{\text{carb}}$ values in Early Medieval Europe fall between -13 to -17‰ which is consistent with C$_3$ based diets. This will be explored in greater detail below and in subsequent chapters, in terms of freshwater versus terrestrial input, whole diet and protein consumption (bone and dentine collagen).

5.2.1.3.2 Bone collagen $\delta^{13}C$ and $\delta^{15}N$

In Figs. 5-19 to 5-22 England, once again, dominates the dataset (48.8%); however the regional trends behind some of the variability in Figure 5-9 are now clearer. Similarities and differences between the regions highlight underlying isoscapes and different consumption patterns across Early Medieval Europe.

*Figure 5-19: Ridge plot of Early Medieval European bone $\delta^{13}C_{\text{coll}}$ values by region, coloured by quartile. NB: all North Atlantic samples here are from Iceland.*
Starting with bone δ\textsuperscript{13}C\textsubscript{coll} values (Figure 5-19 and Figure 5-20), there are clear regional differences between access to and/or consumption of C\textsubscript{4}/marine resources resulting in higher δ\textsuperscript{13}C\textsubscript{coll} values. Greece, Inland and Western Iberia, the Balearic and Tyrrhenian Seas, Croatia, the Po Valley, Austro-Hungary and Bavaria, Scotland and the Scottish Isles and Atlantic and Arctic Norway are all skewed towards C\textsubscript{4}/marine resource consumption, with few individuals in other regions having similar values. The multi-modality seen in regions with C\textsubscript{4}/marine dietary input shows a range of diets from more C\textsubscript{3} based to heavily C\textsubscript{4}/marine based diets. Croatia has the most positive δ\textsuperscript{13}C\textsubscript{coll} values, and it has been suggested that this is due to millet consumption (Vidal-Ronchas et al., 2019). It has generally been assumed, given the δ\textsuperscript{15}N\textsubscript{coll} values below, that most regions in central and eastern Europe, and the Mediterranean have these signatures due to C\textsubscript{4} terrestrial resources (i.e. millet), with some exceptions in Iberia and the Balearic Islands suggesting marine consumption (Alaica et al., 2019; Alexander et al., 2019; Amorim et al., 2018; Bourbon et al., 2011; Bourbou and Richards, 2007; Ciaffi et al., 2015; Dury et al., 2019; García-Collado et al., 2019; Guese et al., 2017; Hakenbeck et al., 2010, 2017; Herold, 2008; Iacumin et al., 2014; Jordana et al., 2019; López-Costas and Müldner, 2016; McGlynn, 2007; Mion et al., 2019; Noche-Dowdy, 2015; Reitsema and Vercellotti, 2012; Salazar-García et al., 2016; Saragoça et al., 2016; Toso et al., 2019; Vidal-Ronchas et al., 2019).
These trends run roughly SE-NW through Europe with $\delta^{13}C_{coll}$ values indicative of $C_4$/marine consumption in eastern Europe and the Mediterranean, with north-westerly regions having clear $C_3$ signals, and more northerly regions with less negative $\delta^{13}C_{coll}$ values again. Austrasia and Burgundy, Normandy/Neustria, Frisia and Saxony, and England all have very similar distributions and IQRs. England’s range is broader than the other $C_3$ regions with more values below -21‰. These individuals could have more freshwater dietary input. The Irish Sea region is also clearly dominated by $C_3$ consumption but is more left skewed which likewise suggests the potential for freshwater resource consumption. The multi-modality in the northern regions (Scotland and the Scottish Isles, Baltic, Skagerrak-Kattegat-Jutland Basin, Atlantic and Arctic Norway and the North Atlantic) is similar to $\delta^{13}C_{carb}$ described above. Given the $\delta^{15}N_{coll}$ values for these regions, this likely reflects marine dietary input rather than $C_4$ resources for those with less negative $\delta^{13}C_{coll}$ values (Barrett and Richards, 2004; Curtis-Summers et al., 2014; Grimes et al., 2014; Howcroft et al., 2012; Linderholm et al., 2008; Müldner et al., 2009; Naumann, Price, et al., 2014; Price et al., 2014; Richards et al., 2006; Sayle et al., 2016; Swenson, 2019; van der Sluis et al., 2016, 2019).

Bone $\delta^{15}N_{coll}$ values are less regionally distinctive than $\delta^{13}C_{coll}$. Many regions have $\delta^{15}N_{coll}$ ranges of 6‰ or more. This suggests that in most regions here, humans varied considerably in their protein consumption, perhaps suggesting differential access to resources. This access could be site dependent (geography and environment) or culturally mediated in some way (e.g. wealth, trade, religious dietary rules). Multimodality in regions further displays trophic level differences in Early Medieval populations (e.g. Greece or Scotland and the Scottish Isles in Figure 5-21). The implication is that those with $\delta^{15}N_{coll}$ values above 8.0‰ have some animal protein in their diets, and those with lower values were consuming little to no animal protein, given the baseline data above (Figure 5-1) and experimental data (Hedges and Reynard, 2007; Minagawa, 1992; O’Connell and Hedges, 1999). The individuals with the highest $\delta^{15}N_{coll}$ values, when coupled with $\delta^{13}C_{coll}$ values of -18.0‰ or above, likely had a large proportion of marine dietary input, a combination of $C_4$ plant foods and a high animal protein diet, or perhaps even ate terrestrial fauna fed on $C_4$ plants, or some combination thereof. Few regions have many, individuals with $\delta^{15}N_{coll}$ values below 8.0‰ but England has the most individuals under this number.
England, when compared to other regions for $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ has broad ranges for both elements (-24.1 to -17‰, and 0.0 to 15.8‰ respectively). However, it has few individuals I would consider as candidates for marine/C$_4$ consumers (defined above as >25% of dietary protein and $\delta^{13}C_{coll}$ values of approx. -18.2‰ or higher, usually with paired $\delta^{15}N_{coll}$ values >10‰). England’s $\delta^{13}C_{coll}$ values therefore largely reflect the native flora of the British Isles. Like other parts of Early Medieval Europe,
England's $\delta^{15}N_{\text{coll}}$ values span several trophic levels with the mean and median (10.0 and 9.9‰) reflective of a population consuming low to moderate amounts of animal protein in their diets.

Ultimately this cross-regional comparison shows a gradient of different foodways and resources (as well as movement of these goods, people and ideas around food) running roughly N-S/SE-NW through Europe.

5.2.1.3.3 Dentine collagen $\delta^{13}C$ and $\delta^{15}N$

The cause for the forked data distribution in Figure 5-10 can be explained by exploring the dentine data regionally. The forked distribution is driven by two sources for higher $\delta^{13}C$ values: C$_4$ diets, and marine-based diets, with the latter having higher $\delta^{15}N$ values as well.

![Ridge plot of Early Medieval European dentine $\delta^{13}C_{\text{coll}}$ values by region, coloured by quartile.](image)

Figure 5-23: Ridge plot of Early Medieval European dentine $\delta^{13}C_{\text{coll}}$ values by region, coloured by quartile.
Croatia stands out again with clear C₄ signals in dentine δ¹³C_coll values since the distribution is heavily skewed to less negative values. A small number of individuals from the Baltic and the Skaggerak-Kattegat-Jutland Basin have dentine δ¹³C_coll values similar to those in Croatia, and approximately half of the Atlantic and Arctic Norway individuals also have C₄/marine signatures based on the thresholds outlined above (>25% estimated input and δ¹³C_coll values ~ -18.2‰). The C₄ influence in the Po Valley is less distinctive in dentine δ¹³C_coll values than in bone, and the bimodality in the distribution supports a population split between C₃ and C₄ resource consumption. The majority of individuals in the Po Valley, England, Scotland and the Scottish Isles, the Baltic and the Skaggerak-Kattegat-Jutland Basin have dentine δ¹³C_coll values consistent with C₃ terrestrial resources. The lowest values around -21‰ could indicate a higher input of freshwater resources or an overall lower trophic position for these people as discussed above.

Regional dentine δ¹⁵N_coll values support my observations above of a more terrestrial C₄ based diet for people in Croatia, and marine based diets for individuals in Fennoscandia, with higher δ¹³C_coll values paired with ¹⁵N enrichment. Scotland and the Scottish Isles, the Baltic, Skagerrak-Kattegat-Jutland Basin and Atlantic and Arctic Norway all have noticeably ¹⁵N enrichment compared to Croatia and the Po Valley. With the exception of the Po Valley (which is remarkably symmetrical in its distribution) all regions have some degree of multi-modality, reflecting my earlier observations of varying trophic levels within regions. England’s dentine δ¹⁵N_coll range
spans the whole western European range and is bimodal. The lower mode reflects diets similar in protein consumption to those in Croatia and the Po Valley, while the higher mode matches well with the values seen in the more northerly regions. This mirrors England’s cultural and geographic position between the old Roman world and the North Sea zone. This may reflect cross-cultural contact with these two regions and their impacts on English foodways and/or the environmental diversity within England. The diets of children in Early Medieval England are somewhere between two climates and two different foodways, which, in light of the high degree of mobility shown in Chapter 6, is not surprising.

Figure 5-25: Ridge plot of Early Medieval European dentine $\delta^{15}N_{\text{dentine}}$ values by region, coloured by quartile.
As mentioned above for enamel, the published data included alongside my own here represent a wide variety of teeth and their varied formation ages; dentine begins forming after the enamel crown and takes longer to complete so represents a longer dietary snapshot (see Table 2-1). Many dentine studies focused on breastfeeding and weaning and therefore early forming and deciduous teeth are therefore a not insignificant part of my dataset – ~9% of dentine samples are from deciduous teeth and ~11% from first molars. As dentine reflects childhood diet, some patterns are certainly impacted by breastfeeding and the osteological paradox, as there are more children in this dataset than in the bone data. Some of the higher dentine δ¹⁵N_{coll} values may also be the result of childhood nutritional stress and health problems (Beaumont et al., 2015; Crowder et al., 2019; Fuller et al., 2005; Swales, 2012).

Survivorship and matched tissues will be investigated in greater detail in Chapter 7. Are these more northerly regions eating more protein in childhood or are there more infants and “stressed” individuals from these regions present? My work is a meta-analysis and as such not sub-setted by tooth type. It is therefore beyond the scope of this study to answer such questions. As with enamel studies, there are problems with scoring and reporting of teeth sampled, but in future work I could investigate this further for particular tooth types. The higher number of datapoints from England when compared to one or two sites in the other regions makes it difficult to extrapolate further for interregional comparisons.
5.2.2 Effects of altitude, latitude and longitude on oxygen isotope values

As discussed in Chapter 2 and displayed in Figure 2-1 there are many factors in the hydrological cycle which impact on \( \delta^{18}O \) variability, particularly altitude, latitude and longitude. Measurements for each of these variables were taken for each site and plotted against individual \( \delta^{18}O \) measurements and linear regressions were applied to test the strength of these relationships.

The linear regressions seen in Figure 5-27 show that each variable accounts for very little variance in \( \delta^{18}O \) in western Europe: 1.8%, 0.2%, 5.3% and 6.7% respectively with longitude having the strongest correlation with oxygen isotope values (although still weak). All these relationships are negative except for latitude, which supports the findings of Lightfoot and O’Connell (2016). Some of these effects on \( \delta^{18}O \) were expected to show stronger trends; however, these trends could be impacted by a high number of migrants from substantially different coordinates to the cemeteries they are buried in. This will be discussed in more detail later.
Figure 5.27: Linear regressions of Early Medieval European tooth enamel δ^{18}O phosphate values by (top-bottom) altitude, latitude, longitude and longitude excluding the North Atlantic islands of Greenland and Iceland.

5.2.3 Effects of geology

Geology is the primary underlying driver of bioavailable strontium and thus of the isotope ratios that are measured in tooth enamel (Bataille et al., 2018; Brown and Brown, 2011: 85–87; Price and Burton, 2012: 94–95). Geology and soil type, alongside other plant growing conditions (e.g. water availability, temperature etc.) affect plant stable isotope values which can be carried up the food chain (Beerling et al., 2018; Bidwell, 1964; Bogaard et al., 2007; Burnham, 1990; Cernusak et al., 2013; Hamerow et al., 2020, 2020; Tieszen, 1991; Van Straaten, 2006; Williard et al., 2005).
I created simplified geology groupings (Chalk, Volcanic/Metamorphic and Other) from the more complex lithology data gathered in the database to investigate their impacts on isotopic values in human tissues at a broad scale. Recent work by colleagues at Oxford suggests that changes in cultivation of different soil types during the Early Middle Ages had significant impacts on crop stable isotope ratios, however this largely affects topsoil (which may have changed considerably over time) and not bedrock (Hamerow et al., 2020). As topsoils are invariably linked to underlying bedrock and have known knock-on effects for agriculture and produce, the impact of bedrock type was tested for both enamel and collagen isotope values (Beerling et al., 2018; Bidwell, 1964; Burnham, 1990; Van Straaten, 2006; Williard et al., 2005).

5.2.3.1 Enamel - $\delta^{18}O_{phosphate}$, $\delta^{13}C_{carb}$ and $^{87/86}Sr$

![Figure 5-28: Scatterplot of European Early Medieval tooth enamel $\delta^{18}O_{phosphate}$ and $^{87/86}Sr$ values by simplified geology group.](image)

This variation in oxygen and strontium is demonstrated in Figure 5-28 with the effect of geology on strontium isotope values showing clearly. Some individuals buried on “other” geologies also have high $^{87/86}Sr$ values, but equally a large number of individuals buried on high bioavailable strontium geologies have low enamel $^{87/86}Sr$ values. It must be acknowledged that the grouping of many bedrock types in the “Other” category masks a significant amount of geological variation; however the main purpose of these simplified categories was to distinguish between geologies.
which should in theory produce high $^{87/86}\text{Sr}$ values and the chalky soils where a large amount of the English cemetery data originate from.

The violin plots in Figure 5-29 and 5-14 suggest that these long tails on chalk and “other” geologies are outliers and may be individuals who spent time on these older volcanic geologies earlier in life, as they do not match bioavailable $^{87/86}\text{Sr}$ values for the cemeteries they were buried in. The opposite may be true for many individuals buried in places that should give higher strontium isotope values (see Figure 5-11, Figure 5-15, Figure 5-16, Figure 5-29 and digital appendices). The differences between Figure 5-29 and 5-30 show that most people buried on chalk in this study are in England. All of the $\delta^{13}\text{C}_{\text{carb}}$ data from chalk geologies in the European dataset are individuals buried in England, and a large proportion of the chalk burials overall. Aside from the absence of non-English $\delta^{13}\text{C}_{\text{carb}}$ data, the $\delta^{18}\text{O}$ chalk distribution shape is the only one significantly affected by the removal of English data as the shape, range and means remain largely the same for “other” and “volcanic/metamorphic” geologies but not for “chalk”. Chalk loses its bimodality when England is removed, and its peak resembles the “other” geological category. The $\delta^{18}\text{O}$ data bimodality from chalk in Figure 5-29 is interestingly largely driven by sites in Kent (see Chapter 8 for further discussion). The lower peak in chalk $\delta^{18}\text{O}$ in England is inconsistent with $\delta^{18}\text{O}_{\text{MAP}}$ values for the south of England where those cemeteries are largely from (British Geological Survey, n.d.; J Evans et al., 2018). Values are more consistent with some individuals on volcanic geologies (which tend to be higher in altitude and many are also further north).

Given the general principles of stable isotope ecology (see Chapter 2) the $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}$ variation seen in different geological zones is likely caused by other geographical factors. Strontium, which is known to vary with bedrock geology, is not wholly consistent with the geologies surrounding cemetery sites. This might suggest migration from more volcanic geologies to chalky and other lithologies and vice versa. In line with agricultural literature we may expect different outcomes for nitrogen and geology in the next subsection.
Figure 5.29: Oxygen, carbon and strontium isotope values (top-bottom) for Early Medieval tooth enamel by simplified geology including England.

Figure 5.30: Oxygen, carbon and strontium isotope values (top-bottom) for Early Medieval tooth enamel by simplified geology excluding England.
5.2.3.2 Bone collagen $\delta^{13}C$ and $\delta^{15}N$

I assessed the impact of geology type on human bone $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ values as above for enamel. Again, the “other” category masks a lot of geological variability, but the main aim was to investigate the impact of chalk and volcanic/metamorphic geology types and their impact on agriculture, rather than all possible lithologies, as that is outside the scope of this thesis. More detailed geological information is available in the databases (see digital appendix).

Given the principles of IA we would expect geology to have a greater impact on food chain $\delta^{15}N$ values than $\delta^{13}C$ (see Chapter 2). There are very few studies linking bedrock and soil $\delta^{15}N$, but the limited evidence suggests that parent geologies could affect soil $\delta^{15}N$ values by 3‰ or more (Amundson et al., 2003; Szpak, 2014).

Geochemistry and plant $\delta^{13}C$ values interact in a complex system, which is not well understood, but C₄ ecosystems appear to foster a reciprocity in soil carbonates and

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**Figure 5-31: Carbon and nitrogen stable isotope values (top-bottom) for Early Medieval bone by simplified geology.**
plant $\delta^{13}C$ values (Cerling, 1984; Chen et al., 2016; Tahmasebi et al., 2017). Volcanic soils in particular are known for their fertility, which is usually due to recent volcanic alluvium rather than bedrock. Volcanic and metamorphic bedrocks do provide a mineral rich growing environment which might affect nitrogen cycling (Amundson et al., 2003; Craine et al., 2015; Dixon et al., 2011; Finch et al., 2002). Soils on calcareous geologies tend to be thin but well-draining (prone to drought), stony and naturally lower in major nutrients. This can cause major changes to plant isotope values if there are no anthropogenic interventions for better agricultural results (Burnham, 1990; Finch et al., 2002, 2014). Ancient topsoils are hard to quantify or reconstruct, and, of course, anthropogenic interference can change stable isotope signals for soils, plants and animals, and therefore in human consumers (e.g. liming, manuring, irrigation) (Bogaard et al., 2007; Hamerow et al., 2020; Lightfoot et al., 2020; Szpak, 2014; Thomsen and Andreasen, 2019). Hence, I use bedrock geologies here as a rough proxy.

Means are within 2‰ of each other for all three geology types for both $\delta^{13}C_{\text{coll}}$ (-20.0, -19.3 and -18.8‰ respectively) and $\delta^{15}N_{\text{coll}}$ (9.5, 10.5 and 11.0‰). This suggests geology may not have a large impact on carbon and nitrogen isotopic values. Increasing values (both mean and max) from chalk to other to volcanic/metamorphic are seen for both $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$. Since these increases co-occur in each geology type, differential resource consumption may be the cause of this pattern rather than bedrock geochemistry. However, the smaller ranges for both carbon and nitrogen of people on chalky geologies may be a result of the limiting nature of these soils on agricultural systems. Teasing apart the cultural and environmental factors may prove difficult without contemporary plant stable isotopes which are better indicators of soils and growing conditions.

5.2.3.3 Dentine collagen $\delta^{13}C$ and $\delta^{15}N$

Despite the smaller sample sizes outside of England, dentine $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$ values mirror the patterns seen above for bone in western Europe – increasing isotope values for both elements across the geological categories (Figure 5-32). Croatian C₄ signatures are particularly prominent in the ‘other’ category for $\delta^{13}C_{\text{coll}}$. Despite the caveats that come with the dentine data, there are clearly some
differences at this broader level which, as discussed for bone, are likely due to a combination of cultural, chronological and environmental factors. These complex interactions result in distinctive dietary signals which are visible across tissues and life stages. This will be explored in greater depth later in this thesis.

Figure 5-32: Carbon and nitrogen stable isotope values (top-bottom) for Early Medieval dentine by simplified geology.
5.2.4 Effects of environment type
Environments were broadly categorised in terms of their proximity to the coast or other kinds of water sources, as well as marine islands. The few “NA” individuals come from burials in Norway where no further information, aside from a non-traceable site name, was available after enquiries, but it is hoped that the work here, especially the cluster analysis later in this thesis, will aid in environmentally classifying and provenancing such individuals.

5.2.4.1 Enamel
Given that variation in strontium isotope ratios from human tooth enamel is driven by geology, it was not included in the analysis of environment type.

5.2.4.1.1 Oxygen

![Figure 5-33: Early Medieval European $\delta^{18}O$ tooth enamel values by environment type.](image)

The hydrological cycle causes variations in $\delta^{18}O$ values, as seen in Figure 2-1. My hypothesis was that different water sources, and access to them for drinking water, would have an effect on tooth enamel $\delta^{18}O$ values. Hence the categorisation of environment types was done predominantly by waterscape. Marine or freshwater resource exploitation was affected by proximity to waterways before the introduction and large-scale production of preserved aquatic foods (e.g. salted fish) and thus I
hypothesise that these environment categories may show differences in dietary isotope values as well.

Figure 5-33 suggests this in the shape of the distributions of $\delta^{18}O$ values arranged by environment type. Although the large ranges in most environments implies that the multifactorial nature of oxygen isotope fractionation at a Europe-wide resolution confounds simple correlations. $\delta^{18}O$ has a multimodal distribution in many environment types (e.g. coastal environments). In the Fennoscandian Fiords, bimodality could reflect the northerly shift in $\delta^{18}O$ values up the Norwegian coast (Figure 5-12), and differing positions along a fiord (closer to the coast or further inland). Similarly, the wide range of riverine $\delta^{18}O$ values may reflect altitude or longitudinal differences along the water courses and across Europe. More localised environments such as saltmarshes and lakes stand out in Figure 5-33 with more constricted ranges. This could be a function of the environments themselves or the smaller sample sizes.

Overall there are no clear relationships between $\delta^{18}O$ and environment type; despite my expectation to see some differences between coastal and inland communities as per Figure 2-1. Variables which affect $\delta^{18}O$ are complex, so it is not possible to tie $\delta^{18}O$ variation to any one factor. There are some trends in line with underlying hydrological principles of $\delta^{18}O$ variation and fractionation, despite similarities in modalities and summary statistics, the distribution shapes of each environment are different.

We must consider how much of this patterning or lack thereof are true indicators of environment, as per the factors mentioned above and in Chapter 2, and how much of this may be complicated by nonlocals in cemetery groups and/or “brewing and stewing”. These questions will be investigated directly later in this thesis.
5.2.4.1.2 Carbon

Enamel $\delta^{13}C_{\text{carb}}$ values are more closely associated with environment type (assuming diet is predominantly derived from local resources) than $\delta^{18}O$ values because they reflect the whole diet rather than solely protein intake (see Chapter 2) and can therefore be of use in human provenancing. Some ecosystems have large ranges (Figure 5-34), most notably rivers and islands with more positive $\delta^{13}C_{\text{carb}}$ values consistent with $C_4$/marine diets. Intriguingly, coastal environments lack this skewness (with one outlier in the Coastal and Fiordland group, which otherwise looks similar to Island and Riverine environs). Compared to the regional $\delta^{13}C_{\text{carb}}$ values (Figure 5-17 and Figure 5-18) these trends are largely caused by individuals from the Fennoscandia & Baltic, Western Mediterranean, Croatia and the Po Valley. Reliance on marine resources or millet consumption (when $\delta^{13}C_{\text{carb}}$ is combined with $\delta^{13}C_{\text{bone/dentine}}$ and $\delta^{15}N_{\text{bone/dentine}}$) has been suggested for these individuals, which makes sense given their historical ecology (Amorim et al., 2018; Dury et al., 2019; Iacumin et al., 2014; Lightfoot et al., 2015; Naumann, Price, et al., 2014; Price et al., 2014; Price and Naumann, 2014; Vidal-Ronchas et al., 2019).

The rest of the dataset has a range of approximately -17 to -12.5‰ which indicates terrestrial resource consumption. The differences in means and modality may reflect differential terrestrial diets in the same way as differences between $C_4$/marine

*Figure 5-34: Early Medieval European $\delta^{13}C_{\text{carb}}$ tooth enamel values by Environment type.*
resources and terrestrial resources are visible. Since $\delta^{13}C_{\text{carb}}$ is reflective of whole diet it can discriminate between terrestrial and aquatic environments, as freshwater organisms (e.g. freshwater fish, shellfish and macrophytes) have more negative $\delta^{13}C$ values than most terrestrial resources, and lipids from freshwater species are depleted in $^{13}C$ which should have a greater impact on $\delta^{13}C_{\text{carb}}$ than $\delta^{13}C_{\text{coll}}$ values in consumers (Apolinarska et al., 2016; Bearhop et al., 1999; Guiry, 2019; Reitsema et al., 2010; Robson et al., 2012, 2016; Taylor et al., 2017).

Fenland and inland populations have bimodality split at around 13‰. This aligns with the peak in coastal and lake environments. Since $\delta^{13}C_{\text{carb}}$ represents whole diet, bimodality in freshwater/estuarine settings with flowing water (i.e. not lakes) could be caused by diets including a range of aquatic and terrestrial resources. The lower peak may represent those individuals who have a greater reliance on aquatic resources with the less depleted values more characteristic of terrestrial resource consumption (Ambrose and Norr, 1993; Bearhop et al., 1999; Guiry, 2019; Kusaka et al., 2015; Loftus and Sealy, 2012; Reitsema et al., 2010).

Therefore, the higher variability seen in $\delta^{13}C_{\text{carb}}$ values from communities closer to large bodies of water, with distinctive peaks in communities with greater access to freshwater resources, can be explained by the larger range of dietary sources available in these environments and different dietary niches for individuals buried in these ecosystems. This will be compared with $\delta^{13}C$ and $\delta^{15}N$ values from bone and dentine collagen in the Chapter 7 to investigate these diet-isotope interactions further. In particular the collagen-apatite models proposed by Lee-Thorp, Sealy and Kenner, and others, will be considered for communities with no suspected C$_4$ consumption and limited marine input such as England (Clementz et al., 2009; Kellner and Schoeninger, 2007; Lee-Thorp et al., 1989; Lewis and Sealy, 2018; Loftus and Sealy, 2012).

5.2.4.2 Bone collagen - $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$

Environmental factors are the main driving forces behind underlying $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$ variation, impacting plants and herbivores as “bio-samplers” and then higher trophic level consumers (see above and Chapter 2 for more detail). $\delta^{13}C_{\text{coll}}$ in humans
(Figure 5-35 and Figure 5-36) shows subtle differences that track environment type. Inland, wetland, saltmarsh and alpine riverine environments are all similar in terms of distribution, IQRs and central tendency (Figure 5-35). Fiordland environments have less negative values which reflects their access to both coastal and inland resources. Lacustrine environments are similarly less negative than inland and wetland environments, showing the complexity of carbon isotopes in these systems (de Kluijver et al., 2014; Dufour et al., 1999; Katzenberg and Weber, 1999). The broad ranges of $\delta^{13}C_{\text{coll}}$ values in riverine, estuarine (coastal and riverine), coastal and island environments are due to $C_4$ consumption in some regions, usually from migrants to these regions, so they are not truly reflective of these ecosystems in Europe. These $C_4$ consuming individuals have shifted the means and medians to slightly less negative values, but the means still reflect what I assume to be local $C_3$ resources with values around -19.5‰ (clearest in Figure 5-35). However, in coastal and island environments some of these values are likely to be reflective of local marine resources.
The distributions of human $\delta^{15}N_{\text{coll}}$ values by environment are all quite different with less alignment seen in the ridge plots than for $\delta^{13}C_{\text{coll}}$ above. As described in the regional patterns, all environment types have the majority of values above $8\%$, indicating some animal protein consumption in these regions. The wide ranges found
in most environments suggests multi-factorial variability, of which environmentally specific fauna is a factor.

![Figure 5-37: Ridge plot of Early Medieval European δ^{15}N bone collagen values by Environment type coloured by quartile.](image)

![Figure 5-38: Violin plot of Early Medieval European δ^{15}N bone collagen values by Environment type.](image)

For instance, we might expect more fish to be consumed by communities who are nearer to large bodies of water. This may be the cause of the right-skewed distributions in fiordland type environments seen in Figure 5-37 and Figure 5-38.
However, it does not explain the relatively lower $\delta^{15}N_{coll}$ values and more constrained ranges in lacustrine environments, unless these lakes were not well-stocked with fish, or the whole food chain in these environments could be depleted in $^{15}N$. Similarly, the highest values found in individuals buried in riverine, estuarine, coastal and island environments could reflect significant aquatic and marine fish or mammal consumption. It could, of course, reflect higher terrestrial protein consumption in these locations, as Figure 5-9 shows that not all high $\delta^{15}N_{coll}$ values correlate with enriched $^{13}C$, or terrestrial protein could be coupled with C$_4$ plant consumption.

Individuals from salt-marsh environments show $^{15}N$ enrichment which supports previous work on Bronze Age individuals from the Severn estuary (Britton et al., 2008). Wetlands sit in between inland and salt-marsh values, which reflects the diversity of these environments and how some coastal wetlands might display similar $^{15}N$ enrichment to salt-masses. This phenomenon could also explain some of the high values found in coastal and estuarine settings.

Coastal settings do not have as much of an impact on overall human $\delta^{15}N$ values as fiordland or salt-marsh environments, which is not what we would expect given the likelihood of sea-spray $^{15}N$ enrichment and greater access to marine resources. This might be the result of cultural prohibitions, agricultural practices of inland cropping and grazing, or any number of factors. $\delta^{15}N_{coll}$ values of under 8‰ are found across a variety of environments, so cannot be easily explained by one environment type or region and may be due to diagenesis (despite data screening) or cultural factors.

Investigation of the impact of environment type on human bone $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ values has highlighted the dominance of native C$_3$ resources in most Early Medieval European diets. It also raises the question why the impact of the access to these resources on Early Medieval human $\delta^{15}N_{coll}$ values in coastal environments outside of Scandinavian fiords are lower than expected.

**5.2.4.3 Dentine collagen - $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$**

There is less dentine data than what was analysed above for bone, so there are fewer environment types represented. Due to the differences in sample sizes the
distribution shapes are less smoothed and bell-shaped compared to bone, but the main findings of $\delta^{13}C_{coll}$ similarities across inland, fenland, coastal and island ecosystems are also present in dentine. Riverine ecosystems have the same central tendency as these other environment types, but the $C_4$ individuals from Croatia make the fourth quartile noticeably elongated compared to the other environments and they flatten the central peaks. This distribution shape and range are very similar to the riverine $\delta^{13}C_{coll}$ values for bone. The less negative skewing of fiordland environments in dentine mirrors that for bone.

![Figure 5-39](image1.png)

*Figure 5-39: Ridge plot of Early Medieval European dentine $\delta^{13}C_{coll}$ values by environment type, coloured by quartile.*

![Figure 5-40](image2.png)

*Figure 5-40: Violin plot of Early Medieval European dentine $\delta^{13}C_{coll}$ values by environment type.*
The same is true for $\delta^{15}N_{coll}$ values, with less smooth and bell-shaped curves, and the general environmental trends mirroring the ones found in bone $\delta^{15}N_{coll}$ values. Inland and riverine environments are very similar, with some bimodality present indicating a distinction between higher and lower protein proportions in diets. Fenland $\delta^{15}N_{coll}$ values are more constrained due to small sample sizes but align well with the central tendencies of other freshwater environments. Fiordland environments show $^{15}N$ enrichment (as they did for bone). The main difference visible for environment types in dentine is the more positively skewed island communities who resemble the coastal and fiordland group more than they did in the bone data. This could be due to the stress and breastfeeding effects mentioned earlier, higher terrestrial or more marine protein consumption in childhood for these individuals or perhaps differences in the cemeteries and individuals sampled (e.g. dentine sampled from mostly deceased children, and bone from adults).

I have found that once again the dentine $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ values mirror those for their bone counterparts. I suggest that in most regions and environments childhood dietary protein consumption is very comparable to adult dietary protein in the Early Medieval western Europe. This will be explored in greater depth in Chapter 7.
Figure 5-41: Ridge plot of Early Medieval European dentine $\delta^{15}N_{dentine}$ values by environment type, coloured by quartile.

Figure 5-42: Violin plot of Early Medieval European dentine $\delta^{15}N_{dentine}$ values by environment type.
5.2.5 Summary of environmental variation in Early Medieval western Europe

For Early Medieval western Europe as a whole I have found that the faunal baselines are largely very similar for the continent and England. There are some regional differences in fish species availability, and some C4 fed herbivores present by in the Balearic and Tyrrhenian region. A lack of good faunal data for many sites and regions makes it difficult to make direct baseline comparisons and offsets for human data in the Early Middle Ages.

In terms of human isotopic variation region, climate, geology and environment type all play a role in shaping underlying patterns. Some of this regional patterning is cultural and shows migration and introduced foodways (e.g. C4 consumers and δ18O variation in Croatia and the Po Valley). Older geologies formed by deep-time volcanic events such as the Fennoscandian Shield and massifs around Europe are the cause for high 87/86Sr values as predicted, with regional trends indicating higher than expected migration from these geologies to others. δ18O variation is perhaps the hardest to tease apart being very multi-factorial. Altitude, latitude and longitude all have small impacts on signatures, and environment type likewise has minimal impact. Therefore, I suggest that the high degree of variation (large ranges and multimodality) within most regions and environment types for δ18O is caused by a high degree of migration and/or “brewing and stewing”.

Human diets are isotopically very similar across much of western Europe during the Early Middle Ages. There are clear C4 signatures in certain regions around the Mediterranean due to migration and introduced crops such as millet. In some northern regions there are individuals with higher marine consumption but the predominant dietary signatures in western Europe are of C3 diets with some variation in the amount of animal protein consumed within communities. Comparisons between tissues shows similar adult and childhood dietary protein signatures which implies resource consumption rarely changed in terms of key protein source or plant photosynthetic pathway during the Early Middle Ages, though there are notable exceptions (e.g. the introduction of C4 crops mentioned above). I have also shown that in C3 environments δ13C_carn is able to possibly detect freshwater resource consumption without the use of sulphur isotopes (although more experimental work
on dietary routing is still needed especially in terms of the lipid portion of the nutrient pool), which has not been previously used in this way in humans.

5.3 Human isotopic variation – England

England has been contextualised within the natural isotopic variability of Early Medieval Europe above. The same methods will be applied here for investigating underlying isotopic variability within England itself. First, I assess the regional isotopic variation within England, followed by the effects of altitude, latitude and longitude on oxygen, and then the effects of geology and environment type.

<table>
<thead>
<tr>
<th>Isotope and Tissue</th>
<th>Minimum (‰)</th>
<th>Maximum (‰)</th>
<th>Mean (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel δ¹⁸O</td>
<td>13.7</td>
<td>20.3</td>
<td>17.4</td>
</tr>
<tr>
<td>Enamel δ¹³C</td>
<td>-16.2</td>
<td>-11.9</td>
<td>-14.1</td>
</tr>
<tr>
<td>Enamel ⁸⁷/⁸⁶Sr</td>
<td>0.7064</td>
<td>0.7205</td>
<td>0.7099</td>
</tr>
<tr>
<td>Bone δ¹³C</td>
<td>-24.1</td>
<td>-17</td>
<td>-20</td>
</tr>
<tr>
<td>Bone δ¹⁵N</td>
<td>0.0</td>
<td>15.8</td>
<td>10.0</td>
</tr>
<tr>
<td>Dentine δ¹³C</td>
<td>-21.6</td>
<td>-18</td>
<td>-19.8</td>
</tr>
<tr>
<td>Dentine δ¹⁵N</td>
<td>6.7</td>
<td>17.9</td>
<td>11.8</td>
</tr>
</tbody>
</table>

Table 5-3: Summary statistics for human IA values in England.

The ranges and means of the human data from England can be seen in Table 5-3. For enamel this is more constrained than the data from western Europe as a whole, especially where carbon and strontium are concerned. However δ¹⁸O values from England represent almost the whole European range which is not what we would expect given natural variation in the Britain (Evans et al., 2012). In terms of bone and dentine, both of these tissues suggest a wide variety of diets and isotopic niches in England.
5.3.1 Regional variation within England

5.3.1.1 Oxygen

![Graph showing regional variation of δ¹⁸O values](image)

Figure 5-43: Early Medieval δ¹⁸O tooth enamel values in England by region, roughly north-south (left-right).

When the data are viewed by region (Figure 3-3 for designations), localised patterns of consumption and mobility are visible. For example, in Figure 5-43 above, the individuals from the Southwest are all from the Ridgeway Hill, Weymouth, mass grave, assumed to all be captured Scandinavian raiders, whose $^{87/86}$Sr values, archaeological and historical context support that claim (Chenery et al., 2014). Given this and the similarities in δ¹⁸O between some Scandinavian regions and Britain (as highlighted above), we can start to look at the shape of each regional distribution, the range, and mean with consideration of their historical contexts to investigate natural versus cultural variation in each subsample. These patterns will also be revisited below, using relative measures compared to absolute δ¹⁸O phosphate values. Later chapters will discuss the archaeological and historical implications of this more closely while this section will describe the trends and suggest some potential explanations.

With the exception of the Southwest, the other regions in Early Medieval England have means within ±1‰ of the overall means from England reported here (17.4‰) and by Evans et al. in 2012 (17.7‰). This may indicate that this is a true mean for
Early Medieval populations in Britain, but how reflective this is of a truly “local” population remains to be seen (Evans et al., 2012). Regional sample sizes vary widely (see Figure 5-43). Regions are in most cases dominated by one or two sites (e.g. the Southwest here being only Ridgeway Hill). Despite these biases, the variations between regions are still informative – for instance the East of England has the largest range despite its small sample size (two sites). This reflects its large spatial coverage and coastal connections, despite a limited modelled drinking water range (-8 to -7‰ (British Geological Survey, n.d.) or -9.4 to -5.5‰ (G Bowen, 2019)). Figure 5-43 shows the East’s unimodality and two outliers around 20‰. There is very strong bimodality in Kent and East Sussex, with bimodality also visible in the Northeast, Wessex, the Upper Thames and Chilterns, Yorkshire and North Lincolnshire, and possible multimodality in the Central and Cambridge and South Cambridgeshire regions too. These two modes divide almost exactly at 17‰ for Yorkshire and North Lincolnshire, Kent and East Sussex, the Upper Thames and Chilterns and Wessex, with the Northeast groups separating at approximately 18.5‰. This multimodality across regions indicates that there is likely a mixture of local and non-local individuals buried in each region, or several local water sources which were significantly different in their δ18O values. Perhaps individuals at the lower end of the range may be from regions with similar δ18Ophosphate to the “Vikings” buried in the Southwest. How far these measurements deviate from site δ18OMAP values is investigated below in the “brewing and stewing” section.
5.3.1.2 Strontium

Figure 5-44: Human tooth enamel $^{87/86}$Sr values from Early Medieval England by region.

Figure 5-44 shows similar patterns to Figure 5-7, Figure 5-15, Figure 5-16 and Figure 5-28 above (overall min = 0.7064, max=0.7205), with most regions displaying left skewness towards lower $^{87/86}$Sr values consistent with local geologies (see digital appendix for site specific geologies). It is assumed here that most individuals at this lower end of the scale are probably local to Britain, given the base map for the island developed by Evans et al. (2010), with most regions sampled having a maximum of 0.7113 (East, Cambridge and South Cambridgeshire, Kent and East Sussex, Upper Thames and Chilterns and Wessex) and the others a maximum of 0.7114. Values of up to 0.7149 are known for regions like Cumbria, Herefordshire and similarly high values are also found in Cornwall and Wales (Bataille et al., 2018; British Geological Survey, n.d.; Evans et al., 2010). The means for each region all fall under the expected maximum for England, and their regionally dominant geologies (0.7105, 0.7103, 0.7101, NA, 0.7087, 0.7093, 0.7097, 0.7090, 0.7114 respectively) which indicates a dominance of burials originating from within these regions (or those with similar geologies).

Given this alongside the $\delta^{18}$O data above there are many non-locals buried in all of these regions. Some of these non-local strontium values are consistent with Southern Britain (and other parts of Europe) but not with their burial sites. Values of up to
0.7221 are known from the Outer Hebrides, and other parts of mainland Scotland go up to 0.7183, so all values above the regional limits of 0.7113 and 0.7114 are consistent with parts of the British Isles and Ireland (Evans et al., 2010, 2012; Ryan et al., 2018; Wilson and Standish, 2016). Therefore, the broad ranges of each region in England are still surprising, given the distances between many of these cemeteries and areas which give higher bioavailable strontium values. As many cemeteries are inland and rural, they were presumably less well connected for long-distance migration. The similarity between high $^{87}/^{86}$Sr outliers and the Ridgeway Hill “Vikings” is promising when considering the possibility of migration from Scandinavia. Other regions with historically attested migration to England during this period include Normandy and Frisia and Saxony, however these would be virtually impossible to separate from other parts of Britain and Scandinavia on the basis of strontium alone given the current data.

As with oxygen, many of these regions have small sample sizes or distinctive site and chronological biases which make it difficult to make further inferences (e.g. predominantly late Roman and fifth-century burials in Wessex or all burials in the Northeast being from the Bowl Hole cemetery).

There is an apparent need for more strontium work to expand the dataset for England and elsewhere and to improve maps of bioavailable strontium across Europe. Greater interpretative power comes from comparing datasets and combining multiple isotopes and tissues. Strontium, oxygen and carbon will be used in different combinations in Chapter 6 to disentangle environmental variation and cultural events by using a hierarchical structure for clustering to aid the analysis of these patterns.
5.3.1.3 Enamel $\delta^{13}\text{C}_{\text{carb}}$

As carbonate analyses on human tooth enamel are less common than phosphate (see Chapter 2) there are fewer data for $\delta^{13}\text{C}_{\text{carb}}$ both in England and across Europe, and the majority of the data for England I produced as part of this thesis. This means that there are regional biases in the English dataset towards Cambridgeshire (due to greater accessibility of local collections), and Kent and East Sussex as my case study region, although care was taken to try to sample burials from as many regions as was possible, following the sampling strategy in Chapter 4.

There are some clear differences between the regions which likely reflect differential resource availability due to environmental factors, and also each region’s migrant histories, as discussed above. The shapes of each regional $\delta^{13}\text{C}_{\text{carb}}$ distribution and their means are highly varied, with most showing multimodality splitting around -14.5 to -13.5‰. Some of these differences may be chronologically biased due to small sample sizes (i.e. one region being represented by one or two sites). Temporal change will be explored in more detail alongside bone and dentine $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}_{\text{coll}}$ in Chapter 7. Bimodality in regions (e.g. the Upper Thames and Chilterns) indicates a split between terrestrial and freshwater based whole diets in childhood. This is exemplified in the East of England where many of the individuals with lower $\delta^{13}\text{C}_{\text{carb}}$ values are buried near Ely and their collagen values also indicate a high freshwater
protein dietary component (Lucy et al., 2009). The Central region has the highest mean, median and overall value for England (-13.4‰, -13.3‰ and -11.9‰) and is the region most skewed towards some C₄/marine input despite being landlocked. I initially thought this was due to the tenth-eleventh century site of Ketton Quarry chronologically biasing the data and showing the impact of the FEH through enriched δ¹³C from increased marine consumption. However, the other Central site – Southam – is much earlier (¹⁴C dates between the seventh-ninth centuries AD) and the individual in grave 2 has the highest δ¹³C_carb value in England. This suggests that this trend is perhaps not due to the FEH but to local resources and foodways. Therefore, given the environmental implications for δ¹³C_carb it is very likely that other regional differences in whole diet are due to locally determined access to resources and dietary choices, and multi-modality may be due to incoming groups (as some of the δ¹⁸O and ⁸⁷/⁸⁶Sr values indicate) or other cultural factors. These will be explored in greater detail in the following chapters.

5.3.1.4 Bone collagen δ¹³C and δ¹⁵N

When the bone data are viewed regionally two main points arise. Firstly, the reliance on C₃ resources is clear across all regions with the majority of individuals having δ¹³C_coll values between -21.5 and -18.5‰ (Figure 5-46 and Figure 5-47). Secondly, there are subtle localised patterns of consumption visible in both δ¹³C_coll and δ¹⁵N_coll values.
5.3.1.4.1 Carbon

Figure 5-46: Ridge plot of Early Medieval bone $\delta^{13}C_{coll}$ values in England by region, coloured by quartile.

Figure 5-47: Violin plot of Early Medieval bone $\delta^{13}C_{coll}$ values in England by region.

Most regions have some degree of multimodality in bone $\delta^{13}C_{coll}$ values, which points to subtle differences in diets such as greater freshwater or marine exploitation by certain individuals or groups. With the exception of some outliers, most regions have very similar $\delta^{13}C_{coll}$ ranges. The East has the largest range of 7.1‰ (2-3 different trophic levels) and the other regions have ranges of 2.0 to 4.6‰ (1-2 trophic levels). The Southwest has the smallest sample size ($n=8$), one person from Poundbury and
the rest are buried at Beckery Chapel and may represent an early monastic community (R Brunning 2017, personal communication, 28 March; Richards et al., 1998). With such a small number of burials from only two sites it is hard to say more about the diet of this region as a whole. Wessex on the other hand has the largest sample size, and a mean (-19.9‰) close to the England-wide mean (-20.0‰). Wessex and the East of England have the most individuals with enriched $^{13}$C. This could be due to localised foodways incorporating a small but not insignificant amount of marine resources into their diet, some trophic level effects, or some incomers from regions with $C_4$/ marine based diets whose $^{13}$C enrichment has been almost entirely swamped by local British $C_3$ resources (or a combination thereof). I have ruled out any direct $C_4$ consumption within England at this time, as there is no archaeobotanical or historical evidence for any $C_4$ plants being imported or grown in Britain during this period, as mentioned in Chapter 2 (Alt et al., 2014; Ganzarolli et al., 2018; Hagen, 2006: 23, 33, 38–39; Hakenbeck et al., 2017). However, when taking into account Figure 5-19 and Figure 5-20, none of these individuals have strong $C_4$/marine signals.

The Upper Thames and Chilterns, Kent and East Sussex, the East, Cambridge and South Cambridgeshire and Yorkshire and North Lincolnshire all have means very close to the England average. These regions, with the exception of the East, also have very similar ranges and distribution shapes – roughly bell-curved with some multimodality in the upper and lower quartiles. For all of these regions, except the East and some of Yorkshire and North Lincolnshire, the implication is a $C_3$ based diet for all individuals.

In the East, whilst the majority of individuals are centred around the median of -20.1‰, the region also has long tails in both directions, boasting both the highest and lowest $\delta^{13}$C$_{coll}$ bone values for England. It has a second, smaller, peak at approximately -19‰ reflecting its higher number of individuals showing $^{13}$C enrichment. Similar secondary peaks are also found in Wessex, the Central region, Yorkshire and North Lincolnshire and the Northeast. As mentioned above, this second less negative peak in $\delta^{13}$C$_{coll}$ could be due to a variety of reasons, but there is no clear evidence for widespread marine based diets in these regions. The four individuals with the highest $\delta^{13}$C$_{coll}$ values in the East are from later churchyard cemeteries on
Castle Hill in Norwich. These individuals also have δ¹⁵N_{coll} values above 10‰, which implies these individuals were possibly marine consumers. Their later dates of approximately the eighth to the thirteenth century make this marine hypothesis more probable, given information about increased sea fishing (Barrett, 2016; Barrett et al., 2004a; Barrett and Richards, 2004; Müldner, 2016; Serjeantson and Woolgar, 2006). If we expand the criteria for "higher" δ¹³C_{coll} values in the East to anything above -19‰, we have 29 individuals (~8% of the East subsample), it gets more interesting. These additional individuals also have δ¹⁵N_{coll} values between 9.6 and 13.9‰, adding to the possibility of low to moderate marine resource consumption over the period of bone formation. What makes this pattern curious is that for all bar three individuals (two from Lakenheath and one from Westgarth Gardens), the burials are from churchyard/monastic sites, ranging from the seventh to the thirteenth century. This tentatively supports Hull’s (2007) hypothesis that the individuals at South Acre, Burgh Castle and Caister-by-Yarmouth were early adherents to Christian foodways and taking advantage of marine resources to adhere to fasting rules. However, the fact that these values are not abundant and widespread in the region, or England more generally, regardless of date, raises questions about the ubiquity and influence of the FEH and Christianity on English marine consumption.

The Central region’s δ¹³C_{coll} distribution is the most skewed towards less negative values, with multimodality, and one outlier at -22.8‰ which is on the low side. As discussed above, the δ¹³C_{carb} patterns of this area are indicative of a small degree of marine input despite being landlocked, but the FEH was discounted as the sole cause of this pattern as these values were present from the seventh century, and not just a turn of the millennium phenomenon. The less negative values for bone δ¹³C_{coll} are however mostly later with 38/40 individuals above -19.5‰ dating to the eighth century or later (Boddington, 1996; Jarman et al., 2018). Perhaps this region has localised foodways and resources reflected in the whole diet trends seen in δ¹³C_{carb}, but protein sources may change chronologically.

In addition to what was described above for Yorkshire and North Lincolnshire, the similarity of the region’s fourth quartile with quartiles three and four of the Central region and the fourth quartile of the East suggests individuals with some possible marine consumption amidst their predominantly terrestrial diets. There are 22
samples with $\delta^{13}C_{\text{coll}}$ values $\geq -19.5\%_o$ (the tail of the distribution). Three of these are from Belle Vue York, one each from Kirkdale and Masham, and the rest are from Fishergate York; all sites with confirmed or suspected Scandinavian settlement and influence (Buckberry et al., 2014; Müldner, 2005; Müldner and Richards, 2007). All individuals have $\delta^{15}N_{\text{coll}}$ values of above 10\%o, date to within the Christian period (majority are eleventh century or later) and are buried either within a churchyard or no more than 2km from a known contemporary church. 18/22 of them are male. These could therefore be adherent Christians, ecclesiastics even, or Scandinavian settlers with FEH foodways mixed in with terrestrial $C_3$ sources over the period of bone formation and remodelling. Few of these individuals have enamel carbonate isotopic data so the settler hypothesis cannot be tested, nor their $\delta^{13}C_{\text{carb}}$ values directly compared, but this could be an avenue for further study.

In the Northeast, a small sample size (n=39) from one cemetery (Black Gate Newcastle) is problematic for regional interpretations. However, at the Black Gate cemetery there appear to be three distinctive $\delta^{13}C_{\text{coll}}$ groupings, all within $C_3$ range. One individual with the highest regional value of -19.1\%o and $\delta^{15}N_{\text{coll}}$ value of 12.1\%o may, like the others discussed above, have a small marine contribution to the diet, or have a higher degree of animal protein consumption, resulting in trophic enrichment for both elements.

Across all regions those with the lowest $\delta^{13}C_{\text{coll}}$ values tend to have low $\delta^{15}N_{\text{coll}}$ values, but they do not always co-occur (Figure 5-9). There are seven individuals with $\delta^{13}C_{\text{coll}}$ values below -21.5\%o combined with $\delta^{15}N_{\text{coll}}$ values below 8\%o, all from Southumbrian regions, but ranging in date from category B (c. 450-580 AD) to H (1066-1200 AD) and a mix of sexes and burial practices. I cannot find a common thread between these individual and their low isotopic values. There are a further nine individuals with $\delta^{13}C_{\text{coll}}$ values $\leq$-21.5\%o and $\delta^{15}N_{\text{coll}}$ values above 8\%o, from a range of sites, regions and with a variety of dates and burial practices. I hypothesise that these have a substantial dietary protein contribution from freshwater resources similar to that suggested for the Westfield Farm Ely cemetery (Lucy et al., 2009).
5.3.1.4.2 Nitrogen

Nitrogen is far more regionally variable than carbon, mirroring the larger scale European comparisons above. This variability suggests that there was more variety in proportions of protein consumption than in type of ecosystems being exploited (i.e. predominantly C$_3$ terrestrial). Few regions have individuals with $\delta^{15}$N$_{coll}$ values less than 8‰, they are mostly in the southern regions and are mentioned above in combination with their $\delta^{13}$C$_{coll}$ values. Generally these individuals are outliers or at
the extremes of regional ranges, and the majority of Early Medieval individuals in England have bone $\delta^{15}N_{coll}$ values above 8‰, consistent with animal protein consumption of varying amounts (Minagawa, 1992; O’Connell and Hedges, 1999; Petzke et al., 2005). Most regional distributions are bell curve-like with varying means, SDs and tails in the data (and outliers) affecting their skewness. There is a slight trend of increasing $\delta^{15}N_{coll}$ values from the southwest to the northeast (Figure 5-49), with the highest overall values in the Central region (15.8‰), and highest mean in the Northeast (11.4‰). Is this due to regionally varied foodways and/or agricultural practices, a product of sampling biases and chronology, underlying environmental variation (e.g. sea-spray effect, soil nitrogen cycling) or some combination thereof? Generally speaking, the burials in the Northeast, Yorkshire and North Lincolnshire, and Central regions are skewed towards later burials (tenth century or later) with few (33/356) burials from periods A to C (Roman to c. 630 AD). Chronology could definitely play a key role in this pattern, but each region will be briefly summarised here and the role of different variables on these trends discussed further below.

The sample size for the Southwest, as above, is too small to extrapolate for the whole region, but the bimodality at Beckery Chapel is interesting if the population was ecclesiastical. There are differences in protein consumption which might suggest dietary laws were not strictly adhered to as more individuals have values above 8‰ than below.

Wessex, Cambridge and South Cambridgeshire have subtle bimodality. Wessex is the most skewed towards lower values, indicating that individuals in the region consumed marginally lower protein overall. The Central region has the most prominent $^{15}N$ enrichment, but this is easily explained by a large number of infants and juveniles analysed in this region, with only four adults having values over 12‰ - two from Raunds Furnells and two from Repton (Beaumont et al., 2018; Haydock et al., 2013; Jarman et al., 2018). Without these younger individuals this region would more closely resemble nearby regions like Yorkshire and North Lincolnshire.

As described above, the lowest $\delta^{15}N_{coll}$ values occur in the East and South of England with no obvious variables uniting these individuals. 86 of the values below 8‰ are
buried in Wessex with many dated too early to consider Christian fasting laws as an explanation for negligible protein consumption.

Few points from the more central and northerly regions drop below 8‰. Considering the δ^{13}C_{coll} evidence above for these northerly regions, only a small proportion of the higher δ^{15}N_{coll} values might show a miniscule amount of marine consumption. The chronological bias, together with latitude, makes it difficult in these regions to distinguish between environmental and cultural factors.

The overall picture in England is one of predominantly C_{3} terrestrial diets, with a hint of some sub-regional diets which may include aquatic or marine resources to a lesser degree. This is supported by the enamel carbonate data above. δ^{15}N_{coll} values increase with latitude and could reflect any mixture of cultural and environmental factors across regions. However, the changes in climate and geology seen from the Southwest to the Northeast surely play a factor alongside the strong chronological bias mentioned above. This highlights the need for more diachronic studies in England to address the imbalance described here.

5.3.1.5 Dentine collagen δ^{13}C and δ^{15}N

Does the regional and environmental diversity seen above for bone δ^{13}C_{coll} and δ^{15}N_{coll} values carry over into dentine as it does for western Europe above? Generally speaking, yes. Despite reduced sample sizes of dentine for most regions compared with bone, we see remarkable similarities between Figure 5-48, Figure 5-49, Figure 5-56 and Figure 5-60 and the dentine data in this section.
Regional $\delta^{13}C_{\text{coll}}$ dentine values in England have smaller ranges than in bone and are missing the lowest values below -22.5‰ seen in bone. However, similar distribution shapes are seen for most regions. The similar central tendencies between Wessex, the Upper Thames and Chilterns, Kent and East Sussex, the East and Cambridge and South Cambridgeshire are still apparent at approximately -20‰. The $\delta^{13}C_{\text{coll}}$ dentine values for these regions are all consistent with C₃ diets. The Southwest is skewed towards more negative values than found in bone for the region. The Central region...
with its larger sample size (predominantly from Raunds Furnells) has a wide range for dentine and the highest $\delta^{13}C_{\text{coll}}$ dentine values for England (maximum of $-18\%_{oo}$), which is mirrored in its $\delta^{15}N_{\text{coll}}$ dentine values. As mentioned above, this may be due to the higher proportion of juveniles and infants in the Raunds sample, the later date of the cemetery which might mean there is a greater chance of some FEH impact on the diets of people, even inland; or it could be due to the unique regional foodways I identified in both the enamel and bone signatures of individuals from both early and late sites in the Central region, or a mixture thereof.

Yorkshire and North Lincolnshire, and the Northeast are skewed in the same direction as the Southwest. This skewness is similar to the bone $\delta^{13}C_{\text{coll}}$ values for these two regions but more pronounced and could reflect freshwater resource consumption given their $\delta^{15}N_{\text{coll}}$ values below.

With some minor differences in distribution shape and modality due to sample sizes, the $\delta^{15}N_{\text{coll}}$ dentine values of regions in England are extremely similar to those seen in Figure 5-48 and Figure 5-49 above. Aside from the Southwest, the same trend of increasing $\delta^{15}N_{\text{coll}}$ values from south to north is seen in dentine as I found in bone. The Southwest is markedly different in its dentine $\delta^{15}N_{\text{coll}}$ distribution compared to bone because of the different sites represented. The bone values are mostly from the Beckery Chapel cemetery, whereas the dentine data are entirely from the Ridgeway Hill “Viking” mass grave. This means the dentine data for the Southwest cannot be used as a “local” dietary signal as these individuals are all Scandinavian incomers (Chenery et al., 2014; Loe, 2014). This is supported by the UML (unsupervised machine learning) analyses in Chapters 6 and 7. The Ridgeway Hill individuals are however useful as a comparison for $^{15}N$ enrichment and assumed Scandinavian-influenced foodways. Of course, these more positive values seen in England could have been caused by any combination of factors, as discussed above (e.g. sea-spray effect, incomers with different diets, differences in environment, agriculture, local foodways etc.). The lack of less negative values in Southwest dentine $\delta^{13}C_{\text{coll}}$ values suggests these individuals were not consuming a high proportion of marine resources during the period of tooth formation. This makes me question FEH interpretations either in England or in other parts of Europe, as the Ridgeway Hill individuals date to the tenth/eleventh century AD where we would hope to see marine dietary signals,
especially in Scandinavians (Barrett et al., 2004a; Barrett and Richards, 2004; Müldner, 2016). This once again speaks to intra-Fennoscandian isotopic variability. As mentioned above for western European regional variation and returning to the faunal baseline data, there are large intra-species and inter-sea variations in marine fish $\delta^{13}C$ which may be due to salinity and food chain differences. The Baltic in particular has marine fish baselines which have more negative $\delta^{13}C$ values than fish from the North Sea/Atlantic (Barrett et al., 2011; Hutchinson et al., 2015; Orton et al., 2011). This could be one explanation for individuals like those at Ridgeway Hill appearing more “terrestrial” in their collagen values (although enamel carbonate, as discussed above, is more complex).

The high number of samples, elongated nature of the Central region’s distribution and high dentine $\delta^{15}N_{coll}$ values certainly reflects the large weaning and childhood diet studies conducted in this region (Beaumont et al., 2015, 2018; Haydock et al., 2013; Moore, 2017).

![Figure 5-52: Ridge plot of Early Medieval dentine $\delta^{15}N_{coll}$ values in England by region, coloured by quartile.](image-url)
Overall, I have found that dentine collagen stable isotope values in Early Medieval England have more constrained ranges than bone, especially for $\delta^{13}C_{\text{coll}}$. However, there are clear regional differences which mirror findings for bone, with a south-north gradient of $^{15}N$ enrichment. The potential causes of this are considered in this chapter and in Chapter 7 but may reflect chronological sampling biases in northerly regions as well as the impact of environmental variation. Despite the variety of teeth sampled for different studies (see digital appendices) the similarities between regional bone and teeth values in England leads me to think that diet through the life course was largely the same in the Early Middle Ages, but this is tested directly in Chapter 7.

5.3.2 Effects of altitude, latitude and longitude on oxygen isotope values

I performed linear regressions on the $\delta^{18}O_{\text{phosphate}}$ values from England, as I did above for western Europe. There are stronger $R^2$ values at this regional level (Figure 5-27). This means more variation in the dataset is explained at this resolution by altitude (5.6%), latitude (11%) and longitude (11%) than at a sub-continental scale, however the trends are still weak, as described by Lightfoot and O’Connell (2016).

Geographical effects on $\delta^{18}O$ values in human tooth enamel appear to be stronger on a local rather than continental scale, presumably due to more localised impacts on hydrology by ecosystems and landscapes. Nevertheless, the multifactorial complexity
of hydrology cycles and human liquid consumption means that even at a smaller scale no one single factor has a strong impact on individual $\delta^{18}O$ values.

![Graph showing linear regression lines for altitude, latitude, and longitude.](image)

**Figure 5-54:** Linear regressions of Early Medieval English tooth enamel $\delta^{18}O_{\text{phosphate}}$ values by (top-bottom) altitude, latitude, longitude.

5.3.3 Effects of geology

The effects of geology on isotope values in England match those described above at a European level, except that no burials on volcanic/metamorphic bedrock were
available for inclusion in the database. The European context for England is therefore extremely important.

5.3.3.1 Enamel - $\delta^{18}O$, $\delta^{13}C$, $^{87/86}Sr$

![Diagram of isotope values](image)

*Figure 5-55: Stable oxygen, stable carbon and strontium isotope values (top-bottom) for Early Medieval tooth enamel in England by simplified geology group.*

It is assumed here that the bimodality for carbon and strontium isotope ratios in “other” geologies is due to the high degree of geological variability that that category masks. The long tails in $^{87/86}Sr$ values for both chalk and other geologies do not match the known bioavailable $^{87/86}Sr$ base maps known for these regions of England, and so represent individuals from older geologies elsewhere in Britain and Europe (Scotland, Wales and Cornwall for instance). The oxygen bimodality on chalk areas in
England continues to be of interest, and, as discussed above, is unlikely to be driven by the bedrock itself; I propose that as chalk preserves skeletal remains very well, the high survival of burials on these geologies gives us a good record of cultural signatures instead. This will be touched on below and in coming chapters.

5.3.3.2 Bone - δ¹³C and δ¹⁵N

![Graphs showing δ¹³C and δ¹⁵N values for Early Medieval bone in England by simplified geology.](image)

*Figure 5-56: Carbon and nitrogen stable isotope values (top-bottom) for Early Medieval bone in England by simplified geology.*

The effects of geology on isotopes values in England broadly match those described above at a European level, with three notable exceptions – no available burials from volcanic/metamorphic bedrock, no individuals with clear C₄/marine δ¹³C values above -17‰, and no δ¹⁵N values above 15.8‰. The lack of C₄/marine consumers means the differences between chalk (n=1015) and other (n=1004) geologies virtually disappear with extremely similarly shaped distributions and means for both δ¹³C and δ¹⁵N values (both -20.0‰ and 9.5 and 10.4‰ respectively). Burials on chalky
geologies in England have an extended $\delta^{13}\text{C}_{\text{coll}}$ range of 7.1‰ compared to 4.7‰ for other geologies when C$_4$ consumers are absent. The differences between the two groups is starker for $\delta^{15}\text{N}_{\text{coll}}$ with other geologies having a higher mean and more pronounced multimodality in higher values. The difference between geologies in terms of range for $\delta^{15}\text{N}_{\text{coll}}$ is negligible at 0.6‰. I do not see a large effect of geology on $\delta^{13}\text{C}_{\text{coll}}$ in human bone in England but there may be a small effect of geology on bone $\delta^{15}\text{N}_{\text{coll}}$ values, seen in the higher mean and multimodality. The European contextual data is therefore key to interpretation. The more pronounced differences seen above in Figure 5-31 between geologies may be coincidental; the substantially higher values in other and volcanic/metamorphic geologies for both $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}_{\text{coll}}$ at a western Europe scale seems to be primarily driven by C$_4$/marine consumption in areas with these geologies when compared with the English data. However, the slightly increased $\delta^{15}\text{N}_{\text{coll}}$ values on other geologies implies some small geologically driven differences, especially given the impact of calcareous soils on plant growth as discussed above.
5.3.3.3 Dentine - $\delta^{13}C$ and $\delta^{15}N$

*Figure 5-57: Carbon and nitrogen stable isotope values (top-bottom) for Early Medieval dentine in England by simplified geology.*

The impact of geology on dentine stable isotope values is similar to what is described above for both western Europe (bone and dentine) and bone from England. With more constrained ranges and no outliers, the $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$ distributions for chalky geologies match those for bone (Figure 5-56). The distribution shapes for ‘other’ geologies closely mirrors the bone and dentine patterns found for western Europe. However, this similarity may be due to the dominance of England in these datasets.

Despite differences in distribution shape and range for geology types $\delta^{13}C_{\text{coll}}$ values (2.3 and 3.6‰ respectively) the means for chalk and other geologies are within 0.3‰ of each other (-20.0 and -19.7‰ respectively). This suggests to me that, although there are a higher number of individuals on other geologies with less
depleted $\delta^{13}C_{\text{coll}}$ dentine values, generally both geologies have similar C$_3$ diets in childhood. $\delta^{15}N_{\text{coll}}$ from ‘other’ geologies on the other hand seems to be reflecting the $^{15}N$ enrichment seen above for the northerly regions. This certainly suggests geology and soil type play a role in human tissue $^{15}N$ enrichment as work on plants indicates (Craine et al., 2015; Hamerow et al., 2020; Szpak, 2014). Although, as mentioned above, I believe chronology may play a large role in this pattern due to the dates of the cemeteries represented in the north of England, but this will be discussed in more detail in Chapters 7 and 9.

5.3.4 Effects of environment type

5.3.4.1 Enamel - $\delta^{18}O$ and $\delta^{13}C_{\text{carb}}$

5.3.4.1.1 Oxygen and the environment in England

![Figure 5-58: Early Medieval $\delta^{18}O$ tooth enamel values in England by environment type.](image)

The effects of environment type on $\delta^{18}O$ values are less clear at an England-wide level than at a European scale. There are some differences in means (although these do not exceed 2‰) and ranges as shown in Figure 5-58. Coastal cemeteries have the largest range, followed closely by inland, fenland and riverine sites, with evidently more variability closer to the coast. This initially seems counterintuitive if the deceased are assumed to be local to the coastal regions, where hydrology would dictate higher $\delta^{18}O_{\text{dw}}$ values. Figure 5-12 gives a 4‰ spread in $\delta^{18}O$ values along English coastlines.
whereas we see almost 7% here. This range is therefore likely due to human action – migration – from maritime travel. The large ranges of other environment types cannot be as easily explained as they are very similar to those seen across the continent, and, as these are more geographically constrained, a high number of non-locals to each of these environs seems likely.

5.3.4.1.2 Enamel $\delta^{13}C_{\text{carb}}$ and the environment in England

![Figure 5-59: Early Medieval $\delta^{13}C$ tooth enamel values in England by environment type.](image)

Patterns in $\delta^{13}C_{\text{carb}}$ by environment type in England agree with those demonstrated above for western Europe. With the populations with high levels of $C_4$/marine food consumption removed we can see a strong bimodality in English riverine populations alongside the fens, with the inland population peak closer to that of the lower peak in freshwater environs. The reverse is true for coastal and island populations. If this was taken out of a broader European context the temptation may be to assume that the peaks correspond to marine and terrestrial resources. However, as discussed above, it is more likely that this instead corresponds to terrestrial versus freshwater lipids and protein, with coastal communities in England having little to no $C_4$/marine input in their diets. If we assume from $\delta^{18}O$ values that there is a high proportion of non-locals at each of these sites, we can take the data further to say the bimodality may show local and non-local childhood diets – the lower $\delta^{13}C_{\text{carb}}$ enamel values representing people who predominantly relied on aquatic resources during the
period of enamel formation, and the higher values those who had a more agrarian terrestrial diet in that period. This will be expanded upon in Chapter 7 with the other dietary data.

5.3.4.2 Bone - $\delta^{13}C$ and $\delta^{15}N$ and the environment in England

5.3.4.2.1 Carbon

**Figure 5-60:** Ridge plot of Early Medieval bone $\delta^{13}C_{\text{coll}}$ values in England by environment type, coloured by quartile.

**Figure 5-61:** Violin plot of Early Medieval bone $\delta^{13}C_{\text{coll}}$ values in England by environment type.
In England the impact of environment type on bone stable isotope values is less homogenous than at a western European scale, especially for $\delta^{13}$C values. Much of the multimodality visible in Figure 5-60 and Figure 5-61 are due to small sample sizes. The environs with sample sizes $\geq 50$ are more comparable with those seen for western Europe as a whole. These environment types (inland, fenland, riverine and coastal) all have a clear main peak close to the overall mean for England $\sim 20.0\%$, with another less-negative peak around $-19\%$ (yellow in Figure 5-61). These peaks are mirrored in the other environment types despite their higher modality. Whilst these higher peaks are $\leq 1\%$ apart from the means, and therefore do not represent a whole trophic level shift, they are significant enough to show up on both ridge and violin plots due to the density of points. As discussed previously, this could be due to a variety of factors but certainly adds weight to differential diets in Early Medieval England which are not strictly environmentally dependent. The broad range of values represented across widely different ecosystems (e.g. coastal and inland) is further proof of this. I found it particularly interesting that the highest $\delta^{13}$C values, which could be consistent with some marine consumption, are not found near the coast but further upriver and inland (Norwich, Repton, Ketton Quarry, Portway Andover and Lankhills as mentioned above).
5.3.4.2.2 Nitrogen

![Diagram](image)

**Figure 5-62**: Ridge plot of Early Medieval bone $\delta^{15}N_{coll}$ values in England by environment type coloured by quartile.

**Figure 5-63**: Violin plot of Early Medieval bone $\delta^{15}N_{coll}$ values in England by environment type.

Despite sample size problems, I found interesting patterns in bone $\delta^{15}N_{coll}$ values by environment type (Figure 5-62 and Figure 5-63). The three most common environment types – inland, riverine and coastal – have wide ranges, whereas less common and more constrained environments such as fens have fewer points and smaller ranges. The broader ranges of the more common ecosystems may be a product of the much larger sample sizes or a reflection of good trade and travel.
routes making a wide variety of resources available for consumption. Likewise, this could make it easier for migrants with more varied foodways preserved in their bones to become buried in these communities. Inland and riverine ecosystems have constrained distribution shapes and means which show clearly in Figure 5-62, presumably due to similar access to both freshwater and terrestrial protein resources. \( \delta^{13} \text{C}_{\text{carb}} \) distributions add depth here, with riverine environments showing bimodality, separating individuals who ate more aquatic protein from those who ate more terrestrial protein. Whereas for inland environments I found \( \delta^{13} \text{C}_{\text{carb}} \) to be almost unimodal at the mixing point between terrestrial and freshwater resources, showing more homogeneity in these communities eating a mixture of both rather than preferring one resource over the other. The large range in \( \delta^{15} \text{N}_{\text{coll}} \) values therefore indicates a wide variety in the proportion of protein in the diets of these people from an array of mostly non-marine sources (with exceptions mentioned above).

Fenland environments have the most positively skewed distribution, which I see as supporting the hypothesis that these communities relied heavily on freshwater resources such as eels. This fits with the \( \delta^{13} \text{C}_{\text{coll}} \) and \( \delta^{13} \text{C}_{\text{carb}} \) values I described above (Lucy et al., 2009). Wetland and estuarine environments have similar patterns to the fens, skewed towards higher \( \delta^{15} \text{N}_{\text{coll}} \) values, \( \text{C}_3 \ \delta^{13} \text{C}_{\text{coll}} \) signatures and \( \delta^{13} \text{C}_{\text{carb}} \) bimodality in fenland and riverine environments (there is no estuarine \( \delta^{13} \text{C}_{\text{carb}} \) data available). This suggests there were communities and individuals within these environments who had more freshwater fish in their diet, and others with more terrestrial animal protein. Not only that, but there were also those who ate proportionally higher amounts of these proteins than others.

Coastal environments are comparatively interesting, having the lowest \( \delta^{15} \text{N}_{\text{coll}} \) peak. This suggests that many of the individuals sampled from coastal cemeteries did not have the same proportion of protein in their diets compared to the bulk of individuals in the other environments; but most people sit above 8‰ so did consume some animal protein. When this is combined with the lack of evidence, I found for marine consumption in coastal communities’ bone \( \delta^{13} \text{C}_{\text{coll}} \) and enamel \( \delta^{13} \text{C}_{\text{carb}} \), the implication is that those living (and dying) near the coast did not regularly exploit marine resources in Early Medieval England.
5.3.4.3 Dentine - $\delta^{13}C$ and $\delta^{15}N$ and environment in England

Whilst not all of the same environment types are represented in the dentine datasets, those which are present, once again, are very similar in their patterning to patterns found in bone from Early Medieval England. As already described, the ranges are smaller for dentine than for bone, with the lowest values for both bone $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ absent in dentine.

With only one individual from island ecosystems I cannot say anything about the environment or English island populations more generally, but this one person’s dentine aligns well with the peak in coastal $\delta^{13}C_{coll}$ values. The shape and quartiles of $\delta^{13}C_{coll}$ distributions for burials in inland and in fenland zones are almost identical for dentine and bone. Inland $\delta^{13}C_{coll}$ values show bimodality starting in the fourth quartile. These less-negative values are intriguing to find in people buried inland. I would expect such values in people who had a small degree of marine input in their diet, but this could also be due to trophic enrichment; environmentally I would give the second option more weight. Fenland dentine $\delta^{13}C_{coll}$ values indicate C$_3$ resource consumption in childhood. I would have perhaps expected to see more depleted values due to the conclusions of Lucy et al. (2009) who suggest a heavy reliance on freshwater resources, especially eels, at Westfield Farm Ely (Bearhop et al., 1999; Guiry, 2019). European eel data from Figure 5-1 (admittedly from Denmark and France not England) show that these fish have $\delta^{13}C_{coll}$ values between -24.4 and -20.5‰, and $\delta^{15}N_{coll}$ values between 7.8 and 10.8‰. So, given prey and consumer offsets (see Chapter 2), these human fenland values for both $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ could be the result of a diet with a considerable amount of eel and other aquatic resources.

Coastal environments are less multi-modal for dentine $\delta^{13}C_{coll}$ than bone, but this may be due to sample size differences, as their means (both ~20‰) and IQRs are very similar. Coastal dentine $\delta^{13}C_{coll}$ values are well within C$_3$ terrestrial ranges. Therefore, individuals buried in coastal environments seem to not have eaten much, if any, marine resources either in childhood or adulthood in Early Medieval England.
Riverine environments are multimodal like inland environments (also seen in bone values) for $\delta^{13}\text{C}_{\text{coll}}$. However, for dentine, individuals buried in riverine ecosystems give a more negatively skewed distribution than the other environments. This is in line with my expectations for aquatic environments with exploitation of freshwater resources causing human collagen $^{13}\text{C}$ depletion. I interpret the higher mode in riverine communities as individuals with more terrestrial-based childhood diets, and the lower mode as more aquatic-based. This kind of environment has the most noticeable difference in $\delta^{13}\text{C}_{\text{coll}}$ between bone and dentine, suggesting a shift to more terrestrial resources through the life course for these individuals.

**Figure 5-64:** Ridge plot of Early Medieval dentine $\delta^{13}\text{C}_{\text{coll}}$ values in England by environment type, coloured by quartile.

**Figure 5-65:** Violin plot of Early Medieval dentine $\delta^{13}\text{C}_{\text{coll}}$ values in England by environment type.
Variation between terrestrial and aquatic based diets in Early Medieval England is further supported by the similarities in shape and modality of dentine $\delta^{13}C_{\text{coll}}$ distributions and corresponding enamel carbonate distributions for each environment type. This reinforces my interpretation that there was minimal local exploitation of marine resources in coastal communities in England as many of the individuals with $\delta^{13}C_{\text{coll}}$ values of around $\geq -18.2\%_0$ tend to be in riverine and inland contexts and not by the coast, so may be migrants (as I will suggest in following chapters). This holds even during the tenth to twelfth centuries when the impact of the FEH is meant to begin, although ambiguity in dating and small sample sizes for later burials makes this tentative. There is $^{15}N$ enrichment in certain regions and environments, but the underlying cause(s) of this do not appear to be a marine diet in most instances. Some explanations for this have been suggested (e.g. sea-spray effect, freshwater resource consumption, increased terrestrial protein consumption or some non-local diets). High dentine $\delta^{15}N_{\text{coll}}$ values (Figure 5-66 and Figure 5-67) could be due to breastfeeding and nutritional stress, as discussed above. However, the similarities with bone distributions for these same environments suggests this cannot be the cause for all high $\delta^{15}N_{\text{coll}}$ values in dentine. The bimodality in inland and riverine environments supports my hypothesis of a combination of freshwater resource rich diets and a variety of terrestrial based diets spanning many trophic levels. Childhood diets in fenland environments are more homogenous than inland or riverine environments and lack values over $12.2\%_0$, with higher values found in the other environment types. Coastal communities have the lowest mean of $10.2\%_0$ which is reflected in the skewness of the distribution.

This suggests the majority of coastal communities had less protein in their diets during childhood than individuals from other environment types. Given the lack of evidence for marine consumption in dentine $\delta^{13}C_{\text{coll}}$ values, the tail of higher $\delta^{15}N_{\text{coll}}$ values in coastal environments could be the result of higher freshwater/terrestrial protein consumption by some individuals, breastfeeding or the sea-spray effect.
Figure 5-66: Ridge plot of Early Medieval dentine $\delta^{15}N_{coll}$ values in England by environment type, coloured by quartile.

Figure 5-67: Violin plot of Early Medieval dentine $\delta^{15}N_{coll}$ values in England by environment type.
5.3.5  Summary of environmental variation in Early Medieval England

In summary, England has a higher degree of variability in both $\delta^{18}$O and $^{87/86}$Sr than expected, given baseline data. This is consistent across most regions, geologies and environment types and contrary to expected environmental variation and baselines. This indicates that there was a good degree of mobility into (and possibly from) England during the Early Middle Ages. This is discussed in more depth in Chapter 6.

Chalk geologies clearly impact isotopic values within England, likely due to their poor growing conditions for crops which is carried up the food chain. There is a lack of clear $C_4$/marine consumption, with only a few individuals showing a small degree of possible marine consumption, but this is not definitive. Diets in England are somewhat regionally dependent with a south-north gradient seen in $\delta^{13}$C_coll and $\delta^{13}$N_coll values. This is tied to environmental variation but also, I suspect, regionally distinctive foodways. Chronology may also play a significant role in these patterns, which I explore further in Chapter 7. Despite this variation, dietary signatures in dentine and bone are remarkably similar, suggesting diets did not change significantly over the life course in Early Medieval England.

Using enamel $\delta^{13}$C_carb values I have found evidence for freshwater fish consumption, which is particularly clear in riverine and fenland environments in Yorkshire and North Lincolnshire, the East, Cambridge and South Cambridgeshire, and the Upper Thames and Chilterns.

5.4  Chapter summary

The aim of this chapter was to categorise environmental variation in faunal and human tissues across Early Medieval western Europe and within England, which I have achieved. There is a high degree of isotopic variability within Early Medieval European populations, driven by a variety of underlying factors, some easier to discern than others. England and Scandinavia dominate the dataset which has implications for interpretations that can lead to circular arguments when trying to discern regional isotopic overlap and mobility between regions. This being said, I have found some distinctive regional patterns, especially in terms of diet.
It is clear that C4 resources were not introduced and consumed widely beyond southern and eastern parts of Europe in our period, consistent with historical narratives and recent research (Alonso et al., 2014; Amorim et al., 2018; Dury et al., 2019; Hakenbeck et al., 2010, 2017; Iacumin et al., 2014; Vidal-Ronchas et al., 2019). Marine resource consumption also appears to be spatially limited, with little to no evidence for it outside of certain parts of Scandinavia, and it is unclear if this is due to cultural reasons (e.g. taboos) or other factors. I discovered freshwater fish consumption in parts of western Europe and England using enamel carbonate values which has not been done for human enamel in this way before. Within England and across western Europe environmental variation impacts dentine and bone collagen signatures almost identically, showing dietary continuity through the life course.

Human enamel oxygen and strontium values do vary with climatic and environmental factors. However, correlations are often weaker than expected and patterns unclear, which highlights the high degree of mobility across Early Medieval Europe and the importance of human behaviour in these complex isotopic signatures. The interplay between climate change and cultural factors will be discussed in the following chapters to better understand, given this underlying variability, how and why Early Medieval people moved and consumed the way they did.
6 Migrants, Mobility, Climate Change and Brewing

In this chapter I continue the meta-analytical work, focussing specifically on isotopic data from human tooth enamel across Early Medieval western Europe, using this to contextualise data from England. Comparing England to its neighbours in terms of isotope values is paramount for identifying movement between regions. Questions around the impact of climate changes such as LALIA and the MWP on human isotope values are also considered here. The larger scale questions of human action addressed in this chapter are:

- Can we see migration between England and the Continent in the Early Middle Ages?
- If so, does migration change over time and how does this align with historically attested events such as the “Adventus Saxonum”, the “Viking Age” and the Norman Conquest?
- Are patterns different between females and males?
- Is “brewing and stewing” a concern for Early Medieval $\delta^{18}$O values and can this be factored into analyses?

I follow the statistical procedures laid out in Chapter 3 to address the questions and aims above; specifically, those focussed on mobility, and aspects of diet preserved in tooth enamel which may be useful for environmental provenancing. I first look at migration and mobility in the Early Middle Ages, before considering the impact of “brewing and stewing” and climate change on oxygen isotopes in human tooth enamel. There are three different elements (and their isotopes) analysed here - carbon, oxygen and strontium. They are considered at varying chronological and regional resolutions. Different aspects of environment, consumption and mobility are explored below, with the broader implications of this discussed in Chapter 9. The same geo-cultural regional sub-divisions from Chapter 5 are used here, as described in Chapter 3 (see Figure 3-2 and Figure 3-3). These allow me to look at localised isotopic patterning which are useful for disentangling environmental variation and isotopic patterning from human actions. Ultimately these comparisons facilitate a better contextualised understanding of the data from England in terms of climate change, migration and culturally mediated fractionation from changes to foodways.
6.1 Migrants and mobility

The primary aim of this chapter is to better understand human migration and mobility during this period of history. Questions around migration events and changes in material culture linked to mobility (especially in burials) have been at the forefront of research into the Early Middle Ages for over a century, being particularly contentious in the 1990s and early 2000s (Bowlus, 1995; Gillett, 2006; Härke, 1998, 2003, 2004, 2007, 2011; Hills, 2013a, 2013b; Pattison, 2008; Thomas et al., 2006, 2008; Winney et al., 2012). Recently, scientific techniques, including (S)IAs, have become part of this debate. Whilst they cannot provide all the answers, they can tackle aspects of these questions which traditional archaeo-historical discourse cannot.

Previous research has largely been done on a site by site basis, which is an approach familiar to many archaeological IA mobility studies. This approach usually identifies outliers from the population based on graphical or statistical distance from the rest of the individuals at a site, sometimes using a local baseline. Whilst this can be useful it is ultimately limiting, as any questions around origin or local versus long-distance migration cannot be addressed with this “odd one out” approach. My research is not the first to use meta-analyses to question how we identify migrants using statistics and baselines (e.g. Evans et al. 2012 or Lightfoot and O’Connell 2016). What is conceptually different here is my statistical approach, which looks at similarities in the data at a broad scale to group individuals together across time and space on the basis of their isotopic signatures, rather than employing outlier procedures. To do so, I have combined more traditional tools, such as boxplots, and statistics like interquartile ranges which help identify outliers (and therefore likely migrants within a community), with hierarchical clustering and machine learning techniques. My approach borrows heavily from methods in ecology and genetics used for finding phylogenetic relationships and community niches. I ask how “related” and tightly clustered isotopic points are to each other (in however many dimensions), working from the individual to the whole dataset, and what defines an isotopic “community” based on statistics and biochemistry.
This section looks at the isotopic evidence for Early Medieval migrants and mobility at a western European scale and then on a regional scale in England. It tackles three major historical migration events to England in the first millennium AD – the so-called “Adventus Saxonum”, the “Viking Age” Scandinavian settlements in England, and the Norman Conquest.

This section first compares isotopic signatures from human tooth enamel across regions to look at similarities, differences and groupings in the data to better understand how these might better inform migration debates. My questions are: how similar are certain regions, and can they easily be distinguished to aid in identifying locals, non-locals and childhood origins? Are there any clear signals of individuals with isotopic signatures which do not match the regions in which they are buried? And, can we observe differential mobility between males and females across the first millennium AD?

6.1.1 Western Europe

Here I use the enamel isotope data from across Early Medieval western Europe to cluster individuals using the underlying variability described above and investigate mobility and migration a priori. Individuals were assigned to clusters in a hierarchical structure using UML (unsupervised machine learning), and the results compared with the geo-cultural designation of the cemeteries. There are significant sampling biases in the dataset which means that many assumptions for common statistical analyses would be violated, e.g. equality of variance (see Chapter 3). The data here are nested and unbalanced, making a hierarchical approach necessary. Therefore, instead of using partitioning clustering methods which require user determination of the number of clusters in the dataset (e.g. k-means), I undertook agglomerative hierarchical clustering using the Ward2 algorithm which I cross-validated using 32 different indices, for more detail see methods in Chapter 3 (Kassambara, 2017; Murtagh and Legendre, 2014; Ward, 1963).

This analysis highlights the human isotopic variability across Early Medieval Europe but also gives a more robust and nested approach to clustering which suits archaeological data and allows researchers to look at groupings in SIA with fewer
assumptions (either statistical or archaeological) imposed. These clusters represent different isotopic niches and can therefore be used to identify migrants which might otherwise be hard to separate using standard graphical and statistical approaches found in many archaeological IA studies. Rather than investigating outliers, cluster analysis looks at the similarities and proximity of individual points, in this case using a hierarchical data structure, giving the researcher the ability to look at relationships between points in a multi-scalar way.

Using the methods outlined above, hierarchical cluster analysis was performed on three combinations of different enamel isotopes:

- Combination 1 ($\delta^{18}O-\delta^{13}C_{\text{carb}}-^{87}Sr/^{86}Sr$); n = 283
- Combination 2 ($\delta^{18}O-^{87}Sr/^{86}Sr$); n = 695
- Combination 3 ($\delta^{18}O-\delta^{13}C_{\text{carb}}$); n = 584

This was done for each combination at a western-European-wide scale, first by looking at each cluster and how it is made up proportionally by individuals buried in each geo-political region, and then secondly looking at each geo-political region in terms of its proportional make up by individuals assigned to each cluster. As the main focus of this thesis is on England, the implications for clustering in other regions of Europe will not be discussed in detail here, except to aid interpretation. It must also be noted that England and Scandinavia dominate much of the enamel dataset and this impacts on the clustering algorithms.

6.1.1.1 Combination 1: oxygen, strontium and carbon

The smallest subset are individuals who have oxygen, strontium and carbon isotope data from the same tooth (n=283). Hierarchical clustering (Figure 6-1) of these data shows three distinctive high-level branches with many subgroups. Cluster validation indices gave a wide variety of outputs for the number of stable clusters, however k=4 had the best support (Appendix F), given the branch structure in Figure 6-1, and the isotopic resolution of the data. The isotopic ranges of each cluster are summarised in Figure 6-1 below and visualised in 3D space in Figure 6-2.
Figure 6-1: Ward’s method hierarchical clustering dendrogram of Early Medieval tooth enamel stable isotope values – with δ¹⁸O, δ¹³C, and ⁸⁷Sr/⁸⁶Sr from the same individuals (n=283).

Figure 6-2: Three-dimensional scatterplot of individuals with δ¹⁸O, δ¹³C, and ⁸⁷Sr/⁸⁶Sr values from tooth enamel, coloured by cluster group as determined by analyses behind Figure 6-1.

These four clusters have wide ranges for δ¹³C and ⁸⁷/⁸⁶Sr, with tighter δ¹⁸O ranges. This is likely due to the sample size and geographical biases of the subset, and the
different order of magnitude at which $^{87}/^{86}\text{Sr}$ is reported despite the data being scaled (i.e. not put into the algorithm as raw isotope ratios, this was done by using the base R function ‘scale’ as required by the ‘hclust’ function, it centres the columns of the data matrix and then scales the numeric columns by dividing the (centred) columns by their standard deviations (Kassambara, 2017; Kaufman and Rousseuw, 2009; R Development Core Team, 2017)). Cluster 1 is the smallest and most distinctive, representing individuals with higher $^{87}/^{86}\text{Sr}$ and, with the exception of one individual, $C_3$ $\delta^{13}\text{C}_{\text{carb}}$ diets, and moderate $\delta^{18}\text{O}$ values. Branches 2 and 3 have similar $^{87}/^{86}\text{Sr}$ ranges but are separated by $\delta^{18}\text{O}$ with cluster 2 at the higher end of the European range, and branch 3 occupying the lower end. The clusters within branch 3 are therefore separated from each predominantly by $\delta^{13}\text{C}_{\text{carb}}$. Individuals with $C_4$/marine diets are represented by cluster 3.1. There are some $\delta^{13}\text{C}_{\text{carb}}$ outliers in clusters 1 and 2, which were put in these groups by the algorithm due to the stronger clustering pull of their other isotopic values as per the ranges in Figure 6-1. The 3D plot Figure 6-2 helps us to visualise the relationships between all three isotope ratios and their bearing on cluster assignments in a similar way to a 2D scatterplot.

The proportions of individuals assigned to each cluster from the geopolitical regions are shown in Figure 6-3. This demonstrates the dominance of some geologies and diets in determining the clusters (i.e. the Baltic and Atlantic and Arctic Norway making up approximately 90% of cluster 1 and the $C_4$/marine consumers from the Po Valley forming approx. 70% of cluster 3.1). Cluster 1 is the simplest in its geopolitical make up as it represents those with the highest $^{87}/^{86}\text{Sr}$ values, so the majority of individuals are from the Baltic, and some from Atlantic and Arctic Norway, and Austrasia and Burgundy. Cluster 2, being the largest, is the only cluster to contain individuals from every region. Cluster 3.2 is also varied in its regional membership. No singular region clearly dominates either cluster 2 or 3.2, and both have similar proportions of individuals from Atlantic and Arctic Norway, the Skagerrak-Kattegat-Jutland Basin and the Irish Sea region.

Cluster 2's large membership from a variety of regions is due to it representing $C_3$ diets from lower $^{87}/^{86}\text{Sr}$ geologies and a large range of $\delta^{18}\text{O}$ values which, when converted to drinking water ($\delta^{18}\text{O}_{\text{dw}}(\text{Chenery})$ -8.3 to -1.8), would equate to the first four levels on Bowen's map of European precipitation values, and climates reaching
from the Mediterranean up to the southern Baltic and Scotland (Figure 5-12). Cluster 3.2 has the second highest number of individuals and regional diversity represented after cluster 2. Cluster 3.2 has very similar $\delta^{13}\text{C}_{\text{carb}}$ and $^{87}/^{86}\text{Sr}$ ranges to cluster 2 but has lower $\delta^{18}\text{O}$ values.

**Figure 6-3:** Proportion of individuals in each $\delta^{18}\text{O}–\delta^{13}\text{C}_{\text{carb}}–^{87}/^{86}\text{Sr}$ cluster coloured by region.

**Figure 6-4:** Proportion of individuals in each region by $\delta^{18}\text{O}–\delta^{13}\text{C}_{\text{carb}}–^{87}/^{86}\text{Sr}$ coloured by cluster, using the same colour scheme as Figures 6-1 and 6-2.

Broadly speaking, we can use branch 3 to identify individuals from cooler and higher altitude climates ($\delta^{18}\text{O}_{\text{dw}}$ (Chenery) -13.9 to -8.0) and distinguish within that branch.
between C₄/marine and C₃ based whole diets. Clusters 2 and 3.2 have higher variability in the regions represented. This is because most regions are similar in terms of lower ⁸⁷/⁸⁶Sr values (see Chapter 5) and because Early Medieval populations in western Europe consumed limited C₄ and marine resources.

Figure 6-4 inverts Figure 6-3. Here we see for each region the proportion of individuals assigned to each cluster. So, given the parameters of each cluster and what is known or assumed about European isoscapes, we can use these clusters to better classify variability in these datasets and therefore proportions of possible migrants. Clusters 1 and 3.1 are good examples for this. The high ⁸⁷/⁸⁶Sr geologies of the Fennoscandian Shield show clearly as cluster 1 in the Baltic burials and in lower proportions in Atlantic and Arctic Norway, and Austrasia and Burgundy. This supports the conclusions of the original researchers who hypothesised these outliers in Austrasia and Burgundy were migrants from the Fennoscandian area (Schuh and Makarewicz, 2016). The higher proportion of cluster 1 in the Baltic versus other parts of Scandinavia is interesting but may be due to larger sample sizes and better skeletal preservation compared to Norway and Sweden which are known to have issues with bone preservation (Kjellstrom et al., 2009; Linderholm et al., 2008; Naumann, Price, et al., 2014; Price and Naumann, 2014). Cluster is 3.1 is dominant in the Po Valley. This is expected, as it is the only region in which a significant number of individuals are assumed to have C₄ diets, in combination with oxygen and strontium isotope ratios (and genetics) that support a central and/or eastern European origin (Amorim et al., 2018). Those individuals from the Po Valley region that were assigned to cluster 2 are therefore interpreted here as “local” to sub-alpine Italy.

The Scotland and Scottish Isles subset contains only the Ardnamurchan boat burial. This is an exceptional burial in many respects and should not be taken as being representative of human isotopic variability in that region (Harris et al., 2017). The Irish Sea has a small sample size (n=12) with individuals with isotope combinations that reflect research interests into “Viking” settlement on the Isle of Man and Dublin. However, the combination of clusters 2 and 3.2 here can neither confirm nor rule out Scandinavian versus local origins as there is a base line split in the Irish Sea region between two major δ¹⁸Oₒ₉₋₅ zones. Some of the higher δ¹⁸O values are outside expected ranges, but to better test Mediterranean links proposed by other
researchers we would need better data from the Mediterranean (Hemer et al., 2013; Knudson et al., 2012; Symonds et al., 2014). The only region to have all clusters represented is Atlantic and Arctic Norway which fits with findings in Chapter 5.

In England, approximately 50% of individuals are assigned to cluster 3.2 (the highest proportion of that cluster in any region), c.40% are assigned to cluster 2, and the remainder to cluster 3.1. The large proportions of clusters 2 and 3.2 are not surprising given they represent C3 diets and geological signatures consistent with, if not England, Britain more broadly (as discussed above). The dominance of cluster 3.2 over 2 is surprising given the range of δ18O values in that cluster and England’s δ18O mean (17.4‰). The lack of cluster 1 is also interesting. Given the sampling bias across this Early Medieval dataset towards finding “Vikings” we might expect some individuals from much higher 87/86Sr geologies to be represented, but their absence could be due to the lower number of individuals with all three isotopes available. The four individuals assigned to cluster 3.1 are from Ketton Quarry. Whilst their values for all three isotopes are not outliers for the cemetery or England, this is a site with suspected Scandinavian migrants, and their inclusion in this cluster may be indicative of that (Evans and Tatham, 2004; Tatham, 2004).
6.1.1.2 Combination 2: oxygen and strontium

Combination 2 ($8^{18}\text{O}-87/86\text{Sr}$) is the isotopic combination from teeth with the largest sample size (n=695). This means that a higher degree of resolution was supported in the dendrogram, with the gap statistic method supporting both k=2 (first max) and k=5 (the global max), both visible in the structure of Figure 6-5 below (see Appendix F Fig F-8 for gap statistic graphical method). 14 indices supported k=3 and k=5 was the next best supported optimal number of clusters from six indices (CH, CCC, Friedman, Rubin, gap statistic global max and elbow, see Appendix F.ii). k=3 when plotted did not give sufficient resolution between high and low $87/86\text{Sr}$ signatures, likely due to the smaller number of individuals with high $87/86\text{Sr}$ values; so I employed Bayesian thinking (incorporating prior knowledge, here about underlying isotopic systems) to resolve this discrepancy between indices, data structure and isotopic niches and used the next best supported number of clusters k=5 which gave this separation in strontium (Appendix F.ii). The results can be seen in Figure 6-5 and Figure 6-6. Choosing the optimal number of clusters is a notoriously elusive and debated area of statistics without clear consensus due to the variety of methods employed (hence 32 indices employed here to look at difference, spread, proximity etc.). In hierarchical clustering methods you will always get “clusters” which range from the individual (here n=695) up to the largest split in the data (here 2 large branches see in Figure 6-5 labelled 1 and 2 in the circles). Therefore, depending on which optimal cluster calculation method, or combination thereof, you favour mathematically, you can subdivide from k=2 to k=695 with varying levels of support at each branching (Charrad et al., 2014; Kassambara, 2017, 2018; Kaufman and Rousseeuw, 2009; Kimes et al., 2017; Levenstien et al., 2003; Murtagh and Legendre, 2014). In Appendix F.ii it is clear that the different indices gave the best support for k=2 to k=5, with marginally different scores between these clusters for some of the indices, but support being very weak for k>5 with the next option after 5 being k=13 with a singular index giving it support. This is the only instance of UML in this thesis where the majority rule, isotopic resolution and dendrogram structure did not resolve easily.
Figure 6-5: Ward’s method hierarchical clustering dendrogram of Early Medieval tooth enamel stable isotope values – $\delta^{18}O$ and $^{87}/^{86}Sr$ from the same individuals (n=695).

Figure 6-6: Scatterplot of $\delta^{18}O$ and $^{87}/^{86}Sr$ from Early Medieval European tooth enamel coloured by cluster number determined by analyses from Figure 6-5.

There are two clear higher order branches (1 and 2), separated by $\delta^{18}O$ predominantly, with branch 1 giving the highest values. The branches are also partially separated by $^{87}/^{86}Sr$, with branch 1 capped at 0.7190, and the higher values all in branch 2 (although cluster 2.2.2 is has a similar $^{87}/^{86}Sr$ range to branch 1). The lower $\delta^{18}O$ values of branch 2 are clear in Figure 6-6, as is the distinctive niche of
cluster 2.1 with $^{87/86}\text{Sr}$ values over 0.7241, well beyond known bioavailable strontium values for the U.K.

Figure 6-7 shows the make-up of each cluster proportionally by region, and Figure 6-8 shows the inverse, regions proportionally by cluster number. More regions are present in this $\delta^{18}\text{O}_{\text{oxygen}}-^{87/86}\text{Sr}$ subset and hence there are more regions represented in each cluster. The bias in the dataset towards England and Scandinavia accounts for these regions dominating this clustering exercise.

The dominance of England in the dataset is clear in all clusters but 2.1, followed closely by Fennoscandian burials. The western European $\delta^{18}\text{O}$ average (17.2‰) is reflected in branch 1 (clusters 1.1 and 1.2) with the highest number of individuals assigned here (see the tight clustering around 17.2‰ in Figure 6-6). However, many of the $\delta^{18}\text{O}$ values in cluster 1.1 are enriched compared to the $\delta^{18}\text{O}_{\text{dw}}$ values of the regions they are buried in. We would expect some of the Frankish and Iberian regions or the Po Valley to dominate cluster 1.1 due to their climates (see Chapter 5), but they account for a small proportion compared to the North and Baltic Sea regions. This could be due to migration, climate change or “brewing and stewing” which are discussed below, using $\Delta^{18}\text{O}_{\text{dw-MAP}}$ values. It certainly appears that the small numbers of individuals from cemeteries in southern Europe assigned to cluster 1.1 represent the “local” component of this group. Low $^{87/86}\text{Sr}$ regions are also represented in cluster 1.1 with the most enriched $\delta^{18}\text{O}$ values, with cluster 1.2 the intermediary between 1.1 and 2.2.2 in terms of $\delta^{18}\text{O}$ values.
Cluster 1.2 is the densest group, due to its proximity to the European mean. Its $^{87}/^{86}$Sr values are mostly below 0.711, however there are a few values up to 0.719 which, according to isotopic baselines in Chapter 5, could be consistent with the highlands of Scotland or massifs in Normandy and Iberia. Clusters 1.1, 1.2 and 2.2.2 all have high geopolitical variability, but the Anglo-Scandinavian research bias is clear. This regional diversity in clusters 1.1, 1.2 and 2.2.2 can be explained by their limited $^{87}/^{86}$Sr ranges which are common throughout Europe, as shown in Chapter 5.
However, as is clear in Figure 6-8, there are mismatches between $\delta^{18}$O ranges in clusters and the $\delta^{18}$O\textsubscript{MAP} values possible in many of the regions. If all burials were local, we would not expect one region to have such diversity in $\delta^{18}$O, and in $^{87}/^{86}$Sr, with perhaps the exception of areas around the Alps.

Cluster 2.1 is similar to cluster 1 identified in Combination 1 above. It is defined by extreme $^{87}/^{86}$Sr values. Cluster 2.1 is dominated by burials from the Baltic with <10% from Atlantic and Arctic Norway and Austrasia and Burgundy. Many of these Baltic burials are assumed to be migrants from Norway and Sweden (Price et al., 2016, 2018, 2019; Wilhelmson and Price, 2017).

In short, higher altitudes, which tend to correlate with older high $^{87}/^{86}$Sr geologies, are represented by clusters 2.1 and 2.2.1, with the highest $^{87}/^{86}$Sr values found in 2.1. Some values similar to those found in 2.2.1 are also present in 1.2 but are coupled with enriched $^{18}$O. Cluster 2.2.2 includes individuals with depleted $\delta^{18}$O values and low $^{87}/^{86}$Sr values.

In Figure 6-8 the Fennoscandian regions all have similar proportions of each cluster (aside from 2.1). The majority of cluster 2.1 can be found in the Baltic, as mentioned above. This is to be expected as it is similar to $\delta^{18}$O—$\delta^{13}$C\textsubscript{carb}—$^{87}/^{86}$Sr cluster 1. All clusters are present in Atlantic and Arctic Norway, the Baltic, and Austrasia and Burgundy despite all of these combinations not being possible locally. There is evidence for a high degree of mobility within the Baltic and North Seas, and along the Rhine. Leaving the enrichment issues posed by individuals at the upper end of cluster 1.1 aside, the presence of cluster 1.2 in all regions is likewise expected. In some cases, this is only possible due to mobility or enrichment, though both appear to be relatively minor in the regions present in this analysis (e.g. mobility from one part of Iberia to another).

Cluster 2.2.1 is dominated by the three Fennoscandian regions in almost equal proportion. This aligns well with the geology and climate for the area. There are also six burials from this cluster in England, two in Austrasia and Burgundy and one in the Irish Sea region, these people are therefore conceivably from Fennoscandia as this cluster is rare and people in other areas are infrequently assigned to 2.2.1.
The absence of many individuals with high $^{87}/^{86}\text{Sr}$ values in Scotland and the Scottish Islands is perplexing given the region’s underlying geologies (British Geological Survey, 2019; Evans et al., 2010). Even considering the relatively lower rainfall and enriched $\delta^{18}\text{O}_{\text{MAP}}$ maps for Scotland, we would expect to see a high proportion of Norse settlers in many parts of the region, given historical and archaeological evidence. So, the absence of cluster 2.2.1 and 2.1 here is strange. Scotland is a small portion of the dataset and has notoriously bad skeletal preservation. The 14 individuals in these $\delta^{18}\text{O}_{\text{MAP}}$-$^{87}/^{86}\text{Sr}$ clusters were buried in Cnip (where the Hebridean geology can yield the highest $^{87}/^{86}\text{Sr}$ values for Britain), Ardnamurchan (discussed above), Westness Orkney (bioavailable $^{87}/^{86}\text{Sr}$ values of up to 0.7105 but theoretically a high Norse migrant base), and Auldhame (in the lowlands near the Firth of Forth, likewise lower bioavailable $^{87}/^{86}\text{Sr}$). As mentioned briefly in Chapters 2 and 5 there may be other confounding factors such as sea spray, high marine consumption and machair soils (carbonate-rich, with similar bioavailable $^{87}/^{86}\text{Sr}$ values to chalk, i.e. close to sea water) which could all pull local and migrant Norse enamel values closer to sea water values (Jones and Mulville, 2018; Lewis et al., 2017; Montgomery et al., 2003; Spooner, 1976).

For England, my main focal point, there is a similar problem where the expected proportion of migrants from higher $^{87}/^{86}\text{Sr}$ geologies are not present, with cluster 2.2.1 existent at low levels. There are almost equal proportions of cluster 1.1 and 1.2 present which is similar to the Irish Sea and Normandy/Neustria, making up ~80% of England burials with paired $\delta^{18}\text{O}_{\text{MAP}}$-$^{87}/^{86}\text{Sr}$. Cluster 2.2.2 makes up 15-20% and the remainder are cluster 2.2.1 (discussed above). Approximately 90% of individuals having low $^{87}/^{86}\text{Sr}$ is what we would expect in England, given its own geologies and those of many regions where migrants might come from besides the higher regions already mentioned. However, this means the range for $\delta^{18}\text{O}$ is still very high, which is not feasible with a local population without “brewing and stewing” or other influences, as already mentioned. The diversity of clusters present in England hints towards a wide variety of possibilities, migration being just one.
6.1.1.3 Combination 3: oxygen and carbon

Combination 3 (n=584) gave the lowest resolution. The validation indices supported 1-3 stable clusters, with k=3 chosen due to the dendrogram structure with support from 11 indices (Figure 6-9, Appendix F). As a consequence, all clusters are very large in membership. Clusters 2 and 3 are very enmeshed in their lower and upper $\delta^{18}O$ values respectively (Figure 6-10), with almost identical $\delta^{13}C_{\text{carb}}$ ranges. These two clusters are representative of C3 diets (and hence most of western Europe) and are instead differentiated on the basis of climate. Cluster 2 has the higher end of $\delta^{18}O$ values, and cluster 3 the lower. Cluster 1 has the broadest $\delta^{18}O$ range, but it represents the tail in $\delta^{13}C_{\text{carb}}$ values and therefore individuals with C4/marine diets or a mixed C3/C4 whole diet.

Figure 6-9: Ward’s method hierarchical clustering dendrogram of Early Medieval tooth enamel stable isotope values – $\delta^{18}O$ and $\delta^{13}C_{\text{carb}}$ from the same individuals (n=584).
Figure 6-10: Scatterplot of $\delta^{18}O$ and $\delta^{13}C_{\text{carb}}$ from Early Medieval European tooth enamel coloured by cluster number determined by analyses from Figure 6-9.

When presented proportionally by region and cluster (Figure 6-11 and Figure 6-12) the trends seen above for the other isotopic combinations are reiterated.

Separating clusters along the lines of $\delta^{13}C_{\text{carb}}$ is extremely coarse. Only large-scale $C_3$ vs $C_4$/marine differences are visible here, probably due to the lack of $\delta^{13}C_{\text{carb}}$ data from a wide variety of regions (see Figure 6-12 for regional sample sizes). Cluster 1 is made up of individuals from Croatia and the Po Valley, along with the Balearic and Tyrrhenian Seas – populations with well attested $C_4$ input or suspected mixture of $C_4$/marine resources (Amorim et al., 2018; Dury et al., 2019; Vidal-Ronchas et al., 2019). There are also six individuals from Scandinavia and one from England as regional outliers.

Clusters 2 and 3 are very similar in their regional proportions. The other hierarchical clustering above already revealed much of the $\delta^{18}O$ value and cluster cross-over in $C_3$ consuming regions. The same regional sampling biases are also still evident. Despite the $\sim7\%$ range in $\delta^{18}O$ represented by cluster 2 and 3 in this combination they are present in almost equal proportions in many regions (Figure 6-12). Intriguingly, in the regions where we might have expected higher proportions of cluster 2 on the
basis of Figure 5-12, we see the opposite. Cluster 1 dominates, followed by cluster 3, both representing $^{18}$O depleted drinking water sources in their enamel values.

As already stated, these populations in southern Europe and the Mediterranean are exceptional cases and not representative of "local" values for either oxygen or carbon. The small group of cluster 2 individuals in the Po Valley may be "local". However, without any likely "locals" from regions expected to give enamel $\delta^{18}$O$_{phosphate}$ values up to 21‰, it is difficult to properly assess the possibility of migration from these regions to other regions with higher than expected cluster 2 proportions versus other factors which could cause $^{18}$O enrichment.
England has one individual from cluster 1 (Ketton Quarry). As discussed above, this region displays the most similarities in cluster proportions to the Baltic and Austrasia & Burgundy. However, considering everything already mentioned, it is difficult to say much more from these $\delta^{18}O$–$\delta^{13}C_{\text{carb}}$ clusters. This combination is simplistic, and might prove more effective if combined with other dietary data and $^{87}/^{86}$Sr data which can tease apart some clusters on the basis of geology.
6.1.1.4 Outcomes of hierarchical clustering

The most intriguing patterns emerged with clustering algorithms for Combination 1 and 2 ($\delta^{18}O - \delta^{13}C_{\text{carb}} - ^{87}/^{86}Sr$ and $\delta^{18}O - ^{87}/^{86}Sr$), with minimal success using only enamel carbonate. I discovered a high degree of overlap between regions in isotopic niches (which was predicted given the baseline data) and a high degree of cluster membership variability with this ultimately being mismatched to our known base maps for $^{87}/^{86}Sr$ and $\delta^{18}O$ in particular.

For England I have found evidence through this analysis for a high degree of migrants from Scandinavia and the Baltic, as well as potential migrants from closer to the Mediterranean and further east in Europe based on the diversity of clusters found in England across all three combinations, many of which have isotopic signatures which are inconsistent with the geological and oxygen baselines for England.

I have used the underlying environmental variation categorised above to define isotopic niches to aide in provenancing Early Medieval burials, disentangling the natural from the anthropogenic. We can see clear migration between England and [throughout] continental Europe during the Early Middle Ages from the variation in clusters present in regions compared with their isotopic baselines. This analysis has also highlighted the need for concern over “brewing and stewing” with the highest $\delta^{18}O$ values one cause for these mismatches between clusters and baseline data.

This UML approach to categorising human isotopic niches or clusters has been a useful exercise. It highlights the need for multi-isotope studies when interested in mobility, the analytical power behind these studies, the interesting outcomes from using unsupervised machine learning methods and therefore the great potential for supervised machine learning in IA. Whilst more data is needed from a variety of regions to help redress the balance between certain research foci which dominate the datasets, hierarchical clustering has produced a more nuanced approach to this meta-analysis and has been helpful in determining some human isotopic niches in Europe.
Recap of main findings:

- High degree of isotope and cluster overlap between regions.
- This variability is at odds with baseline data.
- Therefore, a high degree of migrants and mobility within Early Medieval England and western Europe, and concerns raised over how many ‘migrants’ may actually be “brewing and stewing” signatures due to oxygen baseline mismatches.
- England very similar in cluster make up to Scandinavian and Frankish regions, with potential migrants from these regions and further afield such as the Mediterranean.

6.1.2 Examining historic migration events to England – Adventus Saxonum, Viking incursions and the Norman Conquest

This section tackles the research questions: can we isotopically identify the major migration events of the “Adventus Saxonum”, the Viking incursions and the Norman Conquest? And are there any differences between male and female mobility across the period?

Isotope ratios from tooth enamel from Early Medieval England were explored in the context of western Europe to examine historically attested migration events which have been debated archaeologically for decades (Bowlus, 1995; Gillett, 2006; Härke, 1998, 2003, 2004, 2007, 2011; Hills, 2013a, 2013b; Pattison, 2008; Thomas et al., 2006, 2008; Winney et al., 2012). Hierarchical clustering revealed a high degree of isotopic variability in England, with much overlap between regions. This suggests a degree of long and shorter distance migrations across the continent during the Early Middle Ages (and likely long before). An aim of this work was to investigate three migration events to England: “Adventus Saxonum” (c. 450-550 AD), the Scandinavian raids and settlements beginning in the late eighth century AD (“Vikings”) and the Norman Conquest of 1066AD. Given the supposed origin regions of these migrants in Scandinavia and northern Europe, and the high degree of isotopic similarity between these regions and England, it is unlikely that large scale migrations would be isotopically visible (see Figure 5-11 and Figure 5-12). However, what the hierarchical clustering and other environmental analyses have shown is a higher than expected
degree of isotopic variability in England, given baselines, much of which cannot be explained by environmental factors alone, particularly in $\delta^{18}O$ values.

Since England and Scandinavia dominate the dataset, the clustering is biased towards the North Sea zone. Despite this, it is clear that England’s isotopic diversity is likely due to mobility and other factors such as climate change or “brewing and stewing” affecting $\delta^{18}O$ values. However, this large-scale approach does not take into account chronology so it is hard to tell which socio-environmental changes might be responsible for some or all of this variability. As such, chronological resolution is key to answering my research questions about how these isotopic patterns align with the three major historically attested migration events. With good dating these events should be distinguishable and can add to the debate where genetics has been unable to tease apart these inputs due to issues with the molecular clock and close relatedness of “Germanic” populations (Leslie et al., 2015; Schiffels and Sayer, 2017; Winney et al., 2012). It is also central to disentangling these events and the potential impact of LALIA and the MWP on human $\delta^{18}O$ values for England.

Good chronology is also important when considering changes in consumption and foodways; in this chapter I focus on “brewing and stewing” in particular. Ales and pottages were already a part of Early Medieval foodways; however, there are major socio-economic changes that might be visible isotopically. I hypothesised that there may be more $^{18}O$ enrichment after the seventh century due to the rise in monasticism, the agricultural revolution, and increasing urbanisation. This is due to the historical and archaeobotanical evidence which suggest that monasteries facilitated beer and other alcohols to be made in higher volumes, more consistently and distributed to the broader community (Banham, 1996, 2004: 13–28; Behre, 1999; Frantzen, 2014: 219–231; Hagen, 2006: 199–245, 333–361; Hamerow et al., 2020; Hornsey, 2003: 233–484; Unger, 2013; Woolgar, 2016: 42–60). Around the same time we also see an increase in hops cultivation across western Europe which means that ales have a longer shelf life, and no longer had to be made regularly at household scales (Behre, 1999). From the late seventh century onwards synergistic developments in urbanism and agriculture resulted in changed proportions of major crops which aligns with early evidence of town production sites such as breweries and bakeries, so we might expect to see some increase in tooth $\delta^{18}O$ values due to increased production and

When the $\delta^{18}O$ values for England are arranged chronologically using the date categories set out in Chapter 3, from the Roman period to the Anglo-Norman (and possibly into the Angevin/Plantagenet eras in some areas due to dating difficulties), some trends emerge (Figure 6-13). There are fluctuations in $\delta^{18}O$ values causing changes in the range, means and distribution patterns through time. There is a downwards trend from date category A to C (approx. Roman to mid seventh century AD), with means and medians decreasing and the modality shifting to reflect this. These shifts are small but not negligible (a decrease of 1.5‰ in means and 2.2‰ in range). This demonstrates not only a shift in absolute values but generalised shrinking in range from the Roman period to the early seventh century AD. This aligns well with the post-Roman “Adventus Saxonum” migration events and could indicate incoming migrants as a drop in $\delta^{18}O$ values would be expected with migrants from putative homelands in northern Europe. This decrease could also be the impact of the LALIA beginning in c. 536 AD which would be expected to drop $\delta^{18}O_{dow}$ values and would therefore be reflected in enamel values for individuals growing up during this period of climate cooling.
\(\delta^{18}O\) values appear to increase during categories D/E, D-F and D-H, and also in F-I, with means and modality lower in periods E/F and F/G. There are some issues with chronological resolution, especially with unfurnished graves and burials from the eighth century onwards which accounts for the significant overlap in the later periods, as highlighted in Chapter 3. This sharp rise in values during period D-F is perplexing, it might indicate migration from more southerly “warmer” climates or perhaps “brewing and stewing”. This drop in values for periods E/F and F/G is consistent with Scandinavian settlements in this period. The rise in F/I could be second generation and more “local” signatures closer to the England mean (17.4‰), with a small amount of enriched \(^{18}O\) signatures from Norman elites or similar continental groups, or once again “brewing and stewing”.

At first glance, these trends align with the main transitional events which are the focus of this work – the post-Roman “Adventus Saxonum” of the fifth-sixth centuries and subsequent cultural integration, and LALIA (the decrease in values from A-C), urbanisation and a rise in monasticism influencing increase in ale consumption and/or the onset of the MWP, with perhaps some Norman influence (D/E, D-F and F-I), and the Scandinavian raids and settlement (D-H, E/F and F/G).

These rough chronological trends are encouraging, however since these are absolute values and not relative measures compared to localised drinking water values per site it is hard to tell if these patterns are generalised or driven by certain sites or regions. Since not all geographical regions are represented for all periods these trends could be regionally dependent. Some of these issues can be reconciled by combining date categories into three broader periods - 200BC-450AD (“Roman”), c.350-790AD (“Early Medieval”/“Post-Roman”) and c. 790-1066AD+ (“Viking Age to High Middle Ages”), and also by splitting based on osteological sex (Figure 6-14).

Figure 6-14 shows these broader trends clearly with some differences between the sexes; there is a stark change to bimodality and lower values (overall and mean) in the post-Roman period from the Roman, with an overall positive shift in \(\delta^{18}O\) values from the late eighth century onwards.
Recap of main findings:

- Isotopic evidence to support these three migration events.
- Evidence for either migrants from near the Mediterranean or “brewing and stewing” which will be investigated further below.
- Also, evidence for the impact of LALIA and the onset of the MWP in human $\delta^{18}O$ values.

### 6.1.2.1 Difference between female and male mobility in England through time

Differences in female and male mobility are of interest due to perceptions about exogamy, fostering and blended family structures during the Early Middle Ages, as well as assumptions about migrants during the latter part of the period (i.e. that there were more male “Vikings” in England than female Scandinavian settlers and similarly more Norman male elites and soldiers). The short answer to the question “is there a difference between female and male mobility as seen through isotope values in England through time?” is “yes and no.”

![Figure 6-14: Early Medieval tooth enamel $\delta^{18}O$ values from England by broad date category and osteological sex.](image)

Figure 6-14 shows the ranges and distributions of female, male and un-sexed individuals from the Roman period through to the Anglo-Norman period (combining the date categories seen above in Figure 6-13 into larger periods). Overall, ranges are similar across all three periods, with the biggest differences seen between the Roman period and the earlier part of the Early Middle Ages, particularly with both sexes showing a shift downwards in mean and roughly the same bimodality. Unsexed individuals are displayed above in Figure 6-14 but largely ignored here due to the wide variety in ages and completeness of skeletons which they represent. This makes interpretations of their trends in terms of sex differences or family units difficult. However, their general similarities to the other two categories are interesting.
There seem to be some sex-based differences in mobility during the Roman period, which disappear in the Early Middle Ages, but which reappear, albeit subtly, post-790 AD where different ranges and modalities between the sexes are visible.

I compared females to males across the entire period (Roman to post-Conquest) for the data from England using a BEST test (Bayesian Estimation Supersedes the T Test) which assesses the differences in mean and standard deviation between groups. When these differences span zero, the differences cannot be viewed as being substantially different (Kruschke, 2013). The results (see Appendix D.ii) show very little difference between the two groups in both means (MDM = 0.25) and standard deviations (mode of the difference of SDs = 0.0084), with both measures spanning zero. The posterior predictive means\(^8\) of both sexes are representative of average \(\delta^{18}O\) values across Britain and Europe more generally (Evans et al. (2012) give the average for Britain as 17.7‰, my analysis for England gives 17.4‰), reflecting previous research and base maps, but does not reflect the change over time we can see in Figure 6-14 (G Bowen, 2019; Bowen and Revenaugh, 2003; Evans et al., 2012; Lightfoot and O’Connell, 2016).

When this is broken down by period there are some small differences chronologically (Appendix D). No difference was observed using a BEST test between females and males for the period c.350-790AD, with the MDM (mean of the difference of the means) (0.134) even smaller than the overall score between the sexes (0.25). The same was conducted for the period 790-1066+ AD. Here the MDM was higher (0.388) and spanned zero; however, the difference is still less than 0.5‰, and identical standard deviations were found, despite the differences in overall modality seen in Figure 6-14. BEST tests were also performed to compare females in both periods to each other, and the same with males (Appendix D). Similarly, small shifts were observed through time to those described above. In essence, whilst the distributions change shape through time for females and males, the mean across England does not shift significantly over time, with sex or otherwise (Appendix D). Comparing means and standard deviations here is not accounting for the differences in distribution

\(^8\) In Bayesian statistics posterior predictive distributions (and therefore the means of these distributions) are distributions of possible unobserved values which have been predicted based on the observed or ‘real’ data put into the model, generated here by using Markov Chain Monte-Carlo sampling (Kruschke, 2013, 2014). See Chapter 3 for more detailed statistical methods.
shapes seen above in Figure 6-14, this suggests that although the mean value for England changes little by sex or through time, there are still some gendered mobility trends which do change throughout the first millennium AD.

Figure 6-14 does show differences between males and females in terms of distribution shape and outliers, which changes chronologically. There is a long tale in the male values in the Roman period towards depleted $^{18}$O signatures, with females having more enriched $^{18}$O values. This suggests there may be more male mobility in Roman Britain than female, which is not a surprise given military associations but interesting to note, however more data from Roman cemeteries would need to be included here to investigate further (Chenery et al., 2010; Eckardt et al., 2009, 2015; Leach et al., 2009). What is particularly striking is the overall trend in c.350-790AD towards more depleted $^{18}$O signatures and clear bimodality which is very similar in range and modal peaks in both sexes during this period, with a slightly more pronounced tale towards lower $\delta^{18}$O values in males. This suggests an overall change in $\delta^{18}$O values in this period, which will be discussed in detail below, and similar proportions of males and females with values close to the England mean (17.4‰), and slightly more males in the lower mode with depleted $^{18}$O signatures. This perhaps suggests more males from “colder” climates during the period. The most obvious difference in the Early Middle Ages is between the shape of $\delta^{18}$O distributions in England post-790 AD with a noticeable shift in female values (keeping the bimodality) to more enriched $^{18}$O signatures, whereas the male distribution loses the bimodality (almost trimodal) with the main peak centred at c. 17.2‰ and a noticeable tail of depleted $^{18}$O values. This could be a result of continued and consistent male migration from $^{18}$O depleted regions, and a return of female signatures to more “local” values similar to that seen in the Roman period. Climate change and “brewing and stewing” could also play a role in these shifts, and will be explored more below.

The similarities in means and standard deviations between the sexes in each period do suggest that the chronological shifts might be true signals of isotopic changes within the population as a whole, particularly in the period c. 350-790AD. Since factors which might be responsible for such changes in mean and modality (sample size, climate change, brewing and stewing, and migration) are hard to tackle without
first standardising for regional variation, in the next section relative rather than absolute values for oxygen will be used to try and tease these factors apart.

Recap of main findings:

- No differences between the sexes in terms of mean $\delta^{18}O$ values, but this does not mean that more localised fostering and exogamy weren’t practiced as there are differences in the distribution shapes and modality.
- There is evidence for migrants, but females and males appear to be coming from the same regions in roughly the same proportions.
- The small but not BEST test significant difference in post 790AD could perhaps be small groups of male “Vikings” due to depleted $^{18}O$ signatures.
- Clearest gendered/sex-based trends are visible in the Roman and post 790AD periods.

6.2 Brewing and stewing and implications for mobility

As highlighted in Chapter 2, the impact of consuming brewed and stewed food and drink is a significant concern in interpreting human oxygen stable isotope ratios (Brettell, Montgomery, et al., 2012; Pederzani and Britton, 2019). So, I ask what was the potential impact of “brewing and stewing” on these values?

I adopted the use of Modelled Annual Precipitation (MAP) values for sites from Lightfoot and O’Connell (2016) and used these with enamel values converted to drinking water to create $\Delta^{18}O_{dw-MAP}$ values for each individual. The aim was to see how different each individual’s $\delta^{18}O_{dw}$ value is from the modelled local rainwater value, taking various sources of error and uncertainty into account. Aside from variation and uncertainty introduced by consumption and migration these include:

- Differences between $\delta^{18}O_{\text{carb}}$ and $\delta^{18}O_{\text{phosphate}}$ and unquantifiable uncertainty and error introduced from $\delta^{18}O$ conversions (carbonate to phosphate, corrections, $\delta^{18}O_{\text{phosphate}}$ to $\delta^{18}O_{dw}$ etc.).
- Machine error, which for $\delta^{18}O$ is in the range of ±0.1‰ but may differ between laboratories and machines.

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9 As mentioned in Chapter 3, I used two different equations and compared the results of each with linear regressions below (Chenery et al., 2012; Levinson et al., 1987). MAP values were obtained using the OIPC (GJ Bowen, 2019).
• Inter-laboratory variability discussed in Chapter 4 due to pre-treatment and instrumentation to a maximum of 2‰ for bone, assumed to be less for enamel.

• Physiological differences, individual variability and expected population spread of approximately ±2‰.

• Intra and inter-tooth variability.

As the maximum estimated populational or inter-laboratory variability is ±2‰, any values between ±2‰ should be regarded as probably local (Jay, 2005; Lightfoot and O’Connell, 2016; Pederzani and Britton, 2019; Pestle et al., 2014; White et al., 2002, 2004). ±2‰ is perhaps too narrow given the array of factors above which can introduce error and uncertainty, however I did not want to over-estimate these factors with large error margins as many of them are unquantifiable, so I took the generally accepted 2‰ range for populational and maximum inter-laboratory variability as my starting point here (Jay, 2005; Lightfoot and O’Connell, 2016; Pederzani and Britton, 2019; Pestle et al., 2014; White et al., 2002, 2004). For values above +2‰ we must consider possible “brewing and stewing” effects, as these cooking processes can enrich 18O in this direction through fractionation. Those values below -2‰ are likely to be true migrants, or for certain time periods (e.g. the early sixth century AD) climate cooling events should be considered, as there are no known culturally mediated processes which can alter δ18O values negatively (see Chapter 2) (Brettell, Montgomery, et al., 2012; Pederzani and Britton, 2019).

Δ18O_{dw-MAP} values are a relative measure which helps to correct for regional biases in the data which is especially useful for meta-analyses. Using Δ18O_{dw-MAP} allows researchers to better perceive if changes in δ18O are due to migrants in a cemetery, climate change or “brewing and stewing”, through eliminating analytical noise from the underlying environmental δ18O variation described above. It allows us to investigate mobility especially in contexts where migration/mobility may be relatively small scale and between regions with very similar oxygen signatures. For post weaning teeth this gives us a relative idea of how different δ18O_{dw} estimates are from local signatures for cemeteries, and how much we may need to be concerned about fractionation.
I interrogated the impact of different conversion methods – Levinson and Chenery – on $\Delta^{18}O_{dw\text{-MAP}}$ values and their differential identification of individuals outside $\pm 2\%_0$. I used linear regressions to quantify the offset and identify potential regional differences in each conversion method’s application (see Chapters 3 for equations, Figure 6-15 for whole European model and Appendix E for Levinson violin plots and individual regional models).

Figure 6-15: Scatterplot and linear regression of all Early Medieval European $\Delta^{18}O_{dw\text{-MAP}}$ values for both conversion methods.

Figure 6-15 shows the results of both conversion methods plotted against each other with a fitted generalised linear model (regression line). The slope (0.779) and intercept (0.856) of the model in Figure 6-15 demonstrate an offset between the two methods close to 1%$_0$, and the $R^2$ value (0.97) indicates the model is a good fit for 97% of the data. $\Delta^{18}O_{dw\text{-MAP}}$ values derived using Levinson’s equations are more extreme in both directions than those derived using Chenery’s. This means that use of different equations will certainly impact on data interpretation. I recommend the Chenery et al. (2012) equation as it produces fewer values outside $\pm 2\%_0$ so is less likely to overestimate the number of potential migrants. Since it was calculated using an English dataset it seems to be more constrained and conservative in its estimations. This equation is used for reporting $\delta^{18}O$ values throughout this thesis, so it also provides consistency in reporting here (as mentioned in Chapters 2-4).
The data has what appears to be a second clear line above the fitted model. To identify the potential cause of this I undertook regionally specific linear regressions (Figure 6-16).
Figure 6-16: Linear models with 95% confidence intervals of all Early Medieval European $\Delta^{18}O_{dw-MAP}$ values for both conversion methods by region.
Approximately 3% of the data are a poor fit for the linear regressions in Figure 6-15 and Figure 6-16 and they cause $R^2$ values in Figure 6-16 to drop. I identified these as individuals buried in Fennoscandia and the Baltic Sea regions (and those buried elsewhere who have been identified as likely from this area). These individuals have $\delta^{18}O$ and $\Delta^{18}O_{dw-MAP}$ values which form a separate parallel line to those of other European regression lines, effectively showing a different fractionation equation to those buried in other regions (Daux et al., 2005). This suggests these individuals may fall off the Local Meteoric Water Line (LMWL) for Europe and/or Global Meteoric Water Line (GMWL). This could be caused by several different phenomena including “brewing and stewing”, substantially depleted drinking water (e.g. glacial melt) or climate change. The subtly different line equations for each of the regions with $R^2=1$ also shows a need for better LMWL calculation and incorporation into archaeological IA studies, as well as for increased research using hydrogen isotopes in archaeology to allow for LMWL and GMWL comparisons, as is more commonplace in ecological and forensic literature (Bowen et al., 2005; Bowen and Revenaugh, 2003; Ehleringer et al., 2008; Li et al., 2019; Marchetti and Marchetti, 2019).

As $\Delta^{18}O_{dw-MAP}$ values measure fractionation, individuals who sit on these Fennoscandian regression lines are candidates for either severely depleted or evapoconcentrated water drinkers (either naturally or culturally mediated). Since these modelled lines show predominantly positive $\Delta^{18}O_{dw-MAP}$ values I suggest it is the latter. A better measure of this would be to have regressions based on both oxygen and hydrogen isotopes. Isotopes of hydrogen are not commonly measured in archaeological tissues and mechanisms of its metabolism and diagenesis are still relatively poorly understood, although recent work is promising (Jaouen and Pons, 2017; Reynard and Hedges, 2008; van der Sluis et al., 2019). With the use of $\delta D/\delta ^2H$ or other hydrogen isotopes we can better assess what kinds of fractionated waters humans may be consuming, using evapoconcentration lines calculated from LWMLs (Fraser and Meier-Augenstein 2007; McCluney and Sabo 2010; Brettell, Montgomery and Evans 2012; Bowen et al. 2018; Li et al. 2019). This is outside the scope of the current research but will be touched upon again in Chapter 9 as an avenue for future research.
6.2.1 Western Europe

Given the trends in Figure 6-15 and Figure 6-16 above it is clear that individuals who fall on the Fennoscandian regression line(s) should be easy to distinguish using $\Delta^{18}$O$_{dw-MAP}$ values and that we can be reasonably confident that individuals giving results above $+2\%o$ are more likely to be consuming “brewed and stewed” waters than migrants. However, there are still individuals which have higher $\Delta^{18}$O$_{dw-MAP}$ values but who fall along the central line(s) assumed to be drawn from the GMWL. What is particularly puzzling is why this very different regression line appears predominantly in the Scandinavian and Baltic areas (purple-blue lines Figure 6-16), with outliers or lower $R^2$ values in other regions able to be explained by this trajectory. It is unclear whether this means that there is greater evidence for “brewing and stewing” in Early Medieval Scandinavia or perhaps some unexplored Mediterranean connection or other links which might explain these deviations in the linear regressions but the potential for this approach to better assess migrants and outliers and consider the impact of “brewing and stewing” in a more quantifiable way is promising.

Recap of main findings:

- Choice of conversion equations can significantly over-estimate proportions of “non-locals”.
- Linear models derived from the correlation between Chenery and Levinson derived $\Delta^{18}$O$_{dw-MAP}$ values show that drinking water to human enamel offsets in Fennoscandia are markedly different from the rest of western Europe, which indicates markedly different water sources and consumption patterns.
- Evidence to suggest Early Medieval Fennoscandians fall off the GMWL which is useful for provenancing.
6.2.2 England

I applied these principles regionally and chronologically to England, to start to disentangle the effect of local isoscapes and migration using $\Delta^{18}O_{dw-MAP}$ values. As I found no biochemically distinguishable differences between the mean male and female $\delta^{18}O$ values (see Figure 6-14 and Appendix D for BEST tests), both skeletal sexes were combined here.

![Figure 6-17: $\Delta^{18}O_{dw-MAP}$ values for tooth enamel in Early Medieval England by region.](image)

In Figure 6-17, Figure 5-43 has been re-visualised using $\Delta^{18}O_{dw-MAP}$ values instead of $\delta^{18}O$. The shapes of the regional distributions remain the same; however now cross-regional comparison of mobility should be simplified. Any individuals lying beyond $\pm 2\%$ (outside the dotted lines) are regarded as having non-local drinking water values. There are still some interregional variations in sampling strategies to take into account, although unlike in Figure 5-43, Figure 6-17 clearly shows significant regional differences. If we take the Ridgeway Hill individuals from the Southwest as clear examples of Scandinavians buried in Britain, all bar two individuals fall below the -2\% cut-off for “local” individuals. This is consistent with incomers from that area, including expected overlap in $\delta^{18}O$ between parts of England and Scandinavia.

With this as a small proof-of-concept case study I turn to the other regions. The Northeast stands out more prominently in Figure 6-17 with the largest proportion of individuals above +2\% (70.4\%) and therefore the region with the most individuals
we need to consider the impacts of “brewing and stewing” for. The remaining third of the Northeast individuals fall within ±2‰ and therefore can be considered isotopically “local”. All individuals with values above +2‰ are from the cemeteries of Black Gate Newcastle (seventh-twelfth centuries AD) and the Bowl Hole Bamburgh (seventh-ninth centuries AD). Other researchers have suggested that some of these individuals may be from other parts of Britain or Ireland, given the sites’ archaeological and historical contexts (Evans et al., 2012; Groves, 2003; Macpherson, 2005). However, with MAP values of -8.6‰ and -9.1‰ respectively, $\Delta^{18}O_{\text{dw-MAP}}$ values in excess of +3‰ put individuals closer to values found in Normandy and parts of the Mediterranean and beyond (see Figure 5-12). Whilst this could be possible, the very highest values are extreme for Europe and make “brewing and stewing” a likely alternative hypothesis.

The majority of burials in Yorkshire and North Lincolnshire fall within the “local” zone, and, like the Northeast, all individuals outside of this are above +2‰, but are not as extreme as the Northeast. They could be migrants from other parts of Britain, Ireland or continental Europe, but fractionation from heated liquids must also be considered. Another point to note for this region is that it has the most obvious change in distribution shape from Figure 5-43 to Figure 6-17 with its subtle bimodality now smoothed into one clear peak with tails. This suggests an evening out of local $\delta^{18}O$ signatures from multiple sites by using $\Delta^{18}O_{\text{dw-MAP}}$.

The Central region has a similar mean to Yorkshire and North Lincolnshire, but it has more negative values than the more northerly regions. Over 20% of the values are ≥ 2‰ with the majority of these from Wasperton (16), followed by Empingham (3), Ketton Quarry (2), Southam (1) and Repton (1). Most of these individuals date from the fifth to eighth centuries AD. The highest $\Delta^{18}O_{\text{dw-MAP}}$ values in the Central region indicate origins like the southern coast of Normandy, Southwestern Iberia or parts of the Mediterranean, and, whilst this is possible, fractionation through other means seems more likely. The lack of good osteological or sampling information for many of these skeletons means that breastmilk consumption cannot necessarily be excluded either (Brettell, Montgomery, et al., 2012; Britton et al., 2018; Burt, 2013; Fuller et al., 2006; Haydock et al., 2013). The three individuals in the Central region who lie just outside -2‰ (-2.3, -2.1 and -2.1‰) are so close to the cut-off that an origin in Britain
seems highly likely although this is likely much further north than their burial grounds.

The East of England remains distinctive from the other regions in its range; the two outliers with $\Delta^{18}O_{dw-MAP}$ values close to $+5\%$ are from Westfield Farm Ely. These were originally discounted by Lucy et al. (2009); however, my metanalysis shows that values similar to both their $\delta^{18}O$ and $\Delta^{18}O_{dw-MAP}$ values are found elsewhere in Britain. Such values are found in burials at the Bowl Hole Bamburgh (3), Ireland (3), Norway (2), Birka Sweden (1) and Croatia (14), all of whom do not match local drinking water values. The Croatian individuals have the smallest $\Delta^{18}O_{dw-MAP}$ values which adds weight to the theoretical values for the Mediterranean seen in Figure 5-12. Again, culturally altered water sources must be considered. The four individuals at the other end of the range (two from Stanton and two from Ely) are similar to those found in other, more southerly, regions in England and are consistent with values from Ridgeway Hill, so a mixture of (northern) British and Scandinavian (or similar) origins are possible.

Cambridge and South Cambridgeshire is most similar to Yorkshire and North Lincolnshire in distribution shape, but it is shifted in the opposite direction, with the majority of individuals appearing “local” within $\pm 2\%$. A few fall outside $\pm 2\%$ towards the negative end (and one just above $+2\%$ whom we must consider brewing and stewing for alongside migration). So, a mixed origin population in this region with locals buried alongside non-locals with predominantly “colder” oxygen signatures is again likely.

The bimodality of Kent and East Sussex, Upper Thames and Chilterns and Wessex remains very similar to that seen in Figure 5-43, with all three regions having similarly wide ranges, only outdone by the East. The central tendency of these distributions all align near 0%0 but with varying means. The $\Delta^{18}O_{dw-MAP}$ adjustment means that the bimodality in all three regions falls largely within the $\pm 2\%$ zone; however, the tails match higher values in other regions and the lower values are similar to the Ridgeway Hill mass grave. This implies a true signature of two or more drinking water populations in all three regions. The differences in means may reflect sampling biases (e.g. chronological or choosing to sample “exotic” individuals based
on grave goods), variable local drinking water values, or differential migration histories.

Kent and East Sussex still has the most pronounced bimodality in oxygen isotope ratios of all regions and will be explored in greater detail as the case study region in Chapter 8. Like the East and South Cambridgeshire, it has a mean close to 0‰ (± 0.5‰); however, unlike the other two regions, there is a scarcity of points around the mean, showing true bimodality. This supports the hypothesis that in Kent we have a high proportion of “non-local” individuals with two or even three groups with different drinking water sources represented. The group below the mean is proposed to be migrants from northwest Europe (i.e. Frisia, Saxony and Scandinavia). With the exception of one burial from Finglesham, the other burials with ∆¹⁸O_dw-MAP values above +2‰ from Eastbourne and Ringlemere have been interpreted by the original investigators as possible migrants, some from other parts of Britain, and others as continental “Impious Easterners”, however fractionation was also considered for Ringlemere (Brettell, Evans, et al., 2012; Evans et al., 2012; Hughes et al., 2018).

The Upper Thames and Chilterns region has a mean (1.2‰) which is closer to that of Yorkshire and North Lincolnshire (1.6‰) than to other southern regions, despite the similarities in range and modality described above. 13 of the 51 individuals in the region have values ≤ 0‰, eight of which are possible “Danes” from the mass grave at St John’s College Oxford, the other five coming from Harpenden and Bedfordshire, but only two are lower than -2‰. These two individuals are the most likely migrants from other parts of Britain, Ireland or the north of the Continent. There are 19 individuals over +2‰ from two sites – Abingdon (11 burials, c.950-1450 AD) and Berinsfield (8 burials, c. 400-560 AD). In both cases the original investigators considered these burials, on balance, likely local (if not to these sites to Britain and Ireland), citing isotopic enrichment due to climate change in the case of Abingdon and “brewing and stewing” for Berinsfield (Chambers, 2006; Hughes et al., 2014).

Next is Wessex, whose similarity to other regions in terms of distribution has been described above. The mean and bulk of values are skewed more positively which can be accounted for by this region’s sampling bias towards the late Roman/early post-Roman cemetery of Lankhills which accounts for all of the individuals with ∆¹⁸O_dw-MAP
values above +2‰. This, as with other cemeteries and regions, can be accounted for by a mixture of continental migration or consumption of enriched water sources. There are ten individuals in Wessex with values below -2‰, five from the cemetery at Lankhills and another five from Collingbourne Ducis; their enamel δ¹⁸O₅w values are close to -9‰, which are extreme but not impossible values for modern U.K. ground and well water, and consistent with δ¹⁸O₅w values for much of continental Europe (e.g. southern Scandinavia, Germany, Eastern France, Moravia/Bohemia, see Figure 5-12) (G Bowen, 2019; Bowen and Revenaugh, 2003; Evans et al., 2012; J Evans et al., 2018).

The high degree of overlap in δ¹⁸O between regions in Europe makes interpretation difficult, as has been evident throughout this chapter and Chapter 5. However, Δ¹⁸O₅w-MAP values allow us to determine if δ¹⁸O₅w values beyond ±2‰ are more likely to be due to migration or if other factors such as climate change or “brewing and stewing” should be factored into interpretations.

The Northeast and Southwest, the geographical extremes of the English subset, are also the only two regions to have Δ¹⁸O₅w-MAP means outside the ±2‰ “local” range (+3.0 and -2.7 respectively). For the Northeast, this could be due to a predominance of migrants in the region, or due to effects of “brewing and stewing”. However, the Southwest gives far more compelling evidence both isotopically and archaeologically for migration from Scandinavia, with the other regions falling somewhere on the spectrum in between.

What is abundantly clear in comparing regions from both Figure 5-43 and Figure 6-17 is that there are very regionally different migrant and/or “brewed and stewed” consumption patterns within Early Medieval England. Some of this marries well with historical and archaeological data and will be explored in Chapter 9. However, sampling biases are difficult to see past in some areas, so with improved sample sizes in regions like the East and Southwest, with less bias towards “unusual” burials, and more burials from a greater variety of cemeteries from c. 800AD onwards these patterns can be better interrogated.
Figure 6-18: $\Delta^{18}O_{dw-MAP}$ values for tooth enamel in Early Medieval England by date category.

Figure 6-18 shows $\Delta^{18}O_{dw-MAP}$ values chronologically. The shapes of the distributions remain the same as in Figure 6-13 and Figure 6-14, but the sharp decline seen in Figure 6-13 between category A to C is flattened from A to B. The late sixth and seventh centuries are perhaps more distinct from categories B and B-G, and the patterns from D/E onwards remains largely the same.

There are more individuals above $+2\%o$ in the first four date categories than in categories C to E. This shows consistency from the Roman period to the sixth century and a moderate degree of isotopic enrichment. The number of points below $-2\%o$ increases substantially in category B, with an increased negative modality carried into categories C, C/D, D and D/E (although D/E is very elongated), with almost no points above $+2\%o$ in these categories. From the Roman period through to the late seventh century the majority of individuals are therefore presumed to be local. However, the Roman to immediate post-Roman period are more isotopically enriched, and this enrichment disappears by the early seventh century with isotopically depleted individuals. This drop is interesting and could represent migrants from the “Adventus Saxonum” originating in northwest Europe, or a drop in $\delta^{18}O_{dw}$ values caused by the LALIA event of the mid sixth century, or a combination of both. Not all lower $\Delta^{18}O_{dw-MAP}$ values can be explained by LALIA, as many of the individuals who died in the late seventh/eighth century, given their ages at death,
would not have been alive for LALIA to affect their tooth δ¹⁸O values, but perhaps those in categories B, B-G, or the earliest parts of C could have been.

The elongated range in category D/E, followed by the substantially shifted overall position of D/F is interesting, assuming these individuals are mostly from the East and Northeast of England respectively. These shifts are large and should not be dismissed; category D has a δ¹⁸Odw-MAP mean of -0.9‰ and by D-F this is +3.2‰, which drops across the later period but stays close to +2‰ and individuals in date category F-I having a mean of +2.3‰, and only a small number of individuals from after the seventh century have values below -2‰ (mostly in F/G). This large positive difference between enamel and drinking water values in this latter part of our period could be explained by migration from the continent, “brewing and stewing”, or in part by the onset of the MWP. However, although increased Δδ¹⁸Odw-MAP values before 950AD could be due to the steady increase of the MWP, these are not expected to peak before 1000AD and so culturally mediated δ¹⁸Odw enrichment seems more likely for the extreme values, possibly exacerbated by drinking water already elevated by climate change (Chambers, 2006; Fricke et al., 1995; Mann, 2002; Mann et al., 2009). For the individuals below -2‰ from the eighth century onwards, the most expedient explanation would be incoming individuals from Scandinavia due to the “Viking” raids and settlements of this period, although their numbers are far lower than we would expect, given the historical and archaeological evidence. This could be due to Atlantic and Arctic Norway δ¹⁸O signatures being more isotopically visible than those of the Jutland peninsula and parts of southern Scandinavia (see Chapter 5 and baselines in Figure 5-12). Issues with sample size and research agendas may be behind this discrepancy too. Ideally sites or catchments with the full breadth of time (Roman to post Norman Conquest) and good numbers of burials, as well as fauna, could help address these concerns, but the archaeological record is rarely so obliging.

Finally, the periods were combined into bigger categories to investigate larger scale chronological shifts with more robust sample sizes. A greater variety of regions are now represented but sexes are not separated (due to their similarities in means and standard deviations see above and Appendix D).
Despite the disappearance of some century or sub-century level trends between Figure 6-13 and Figure 6-18, the overall chronological trend in both is clear at a larger scale in Figure 6-19. Here we can see the downwards shift between the Roman to post-Roman phases in $\Delta^{18}O_{dw-MAP}$ values with the tail in the first phase becoming the focus of a more populated second mode from the fourth/fifth century. The differences in means of each date category (0.9, 0.2 and 1.9‰ respectively) and overall ranges (8.2, 9.5 and 12.2‰) do not appear large between the Roman and post-Roman phases but we see a jump in the later phase for both indices. The changes in distribution shape and IQRs, as highlighted by the violin and box plots in Figure 6-19, are also noteworthy. The shifts in mean are symptomatic of these larger changes in the descriptive statistics of each date category, with the Roman period having a much tighter IQR and peak around the median, while the post-Roman period of c. 350-790 AD has much wider IQRs and clear bimodality centred below its median, in the region of the tail in the Roman phase. As seen in Figure 6-13 and Figure 6-18 the majority of individuals in both pre-790AD categories are isotopically enriched, however there is an increase in depleted individuals in the post-Roman phases, with both having the majority of individuals within the “local” range for each cemetery ±2‰, and points outside this range as described previously. With a mean of 0.2‰, it is clear that the immediate post-Roman period maintains a large degree of population.
continuity in terms of “local” individuals and the first more positive mode from the Roman period, but also the extended IQR towards -2‰ and a second mode well below the mean shows an increase in individuals from isotopically depleted regions (compared to burial place) which could be migrants.

The increase in $\Delta^{18}O_{dw-MAP}$ values, with a mean close to +2‰ and wider range from 790AD onwards is starkest in Figure 6-19. A BEST test between c. 350-790AD, and 790-1066+AD $\delta^{18}O$ values shows a small MDM (-0.455‰) which does not span 0, so this increase in mean absolute values is small and distinguishable using Bayesian methods but not necessarily biologically meaningful. However, a BEST test between these same periods using $\Delta^{18}O_{dw-MAP}$ values gets around this persistent problem of British and European wide $\delta^{18}O$ means, producing an MDM of -1.75‰ which does not span 0 (group means of 0.153 and 1.91, Appendix D). The similarity in modes and sample sizes for both periods supports this difference in means, and distributions over time as a real, and more importantly a biologically significant, change. This shows that there is a shift from individuals on average having $\Delta^{18}O_{dw-MAP}$ values (and thus $\delta^{18}O_{dw}$ values) which are consistent with being “local” to the cemetery in which they are buried, to individuals post-790AD, on average, having higher $\delta^{18}O_{dw}$ values compared to the locales of their cemeteries. So, whilst mean $\delta^{18}O$ values do not change much through across the first millennium AD in England, the mismatch between $\delta^{18}O$ values in human teeth and their place of burial increases. This is an interesting conundrum, as it raises more questions about human palaeoecology than necessarily answering my initial questions about mobility and Early Medieval transitions. To what extent these patterns are more indicative of climate change, human movement, or changes in foodways (“brewing and stewing”) will be explored in later chapters.
Recap of main findings:

- $\Delta^{18}O_{dw-MAP}$ values give more localised measures of “locals” vs. “non-locals” and allow researchers to better judge potential “brewing and stewing” influences.
- Clear regional trends of migration and culturally mediated fractionation in Early Medieval England
  - Higher numbers of possible “brewed and stewed” individuals in the North
  - Clear evidence for migrants from northern Europe and Scandinavia in many regions, especially the southeast
  - Bimodality in many regions may indicate mixed local and migrant cemetery communities
- Chronologically difficult to completely disentangle evidence for LALIA and “Adventus Saxonum” but evidence for both events and major shift in post-Roman England.
- Evidence for a “brewing and stewing” horizon in the late seventh to eighth centuries AD which coincides with centralised monastic and urban brewing and changes to agriculture to support such centralised provisioning.
- Smaller than expected, but still present, evidence for Scandinavian settlements during the “Viking Age”, likely due to isotopically invisible southern Scandinavians versus isotopically visible Atlantic and Arctic “Norwegians”.
- Evidence for the MWP in human tooth values alongside “brewing and stewing”.

6.3 Summary of the Human Tooth Enamel Meta-analyses

England and Scandinavia dominate the dataset which has implications for interpretations that can lead to circular arguments when trying to discern regional isotopic overlap and mobility between regions. This thesis shows that multi-isotope studies are extremely useful for provenancing archaeological humans and investigating questions of mobility, climate change and consumption. Multivariate isotope data when used with UML demonstrates this high degree of variability but also shows clear mobility across western European in the Early Middle Ages. The lack of clearly identifiable marine consumers in Anglo-Scandinavian England and multimodality in $\delta^{13}C_{\text{carb}}$ values has interesting implications for the “Fish Event Horizon”
which will be discussed further with other dietary IA data in the following chapters (Barrett et al., 2004a, 2004b; Müldner, 2016).

In this chapter I aimed to investigate the major historically attested migration events into England during the period, and what if any impact “brewing and stewing” or climate change may have had on δ¹⁸O values in England as per the research questions set out in Chapter 1. The result is complex and multi-factorial, with chronological change clear in both δ¹⁸O and Δ¹⁸O_dw-MAP values, with a particularly stark shift around the late eighth century AD. I have shown evidence for the “Adventus Saxonum” as well as some impact from LALIA on human tooth δ¹⁸O values. Continued migration from “colder” regions is clear throughout the late sixth and into the seventh century with a sharp change in Δ¹⁸O_dw-MAP values in the eighth century likely linked to changing foodways (“brewing and stewing”). There is less evidence for “Viking” and Norman settlers than expected, perhaps swamped by the enriched ¹⁸O consumption; and the onset of the MWP is possibly present amidst the “brewing and stewing” signature. Interestingly I found no differences between the means and standard deviation of female and male δ¹⁸O values throughout the period. However, the modality and ranges do show sex-based differences in the Roman and post-790AD periods. Across the first millennium AD there appears to be more men with depleted ¹⁸O signatures, even in c.350-790AD when male and female δ¹⁸O distributions and summary statistics are almost identical. It is also likely that more localised fostering and exogamy were practiced, but it may require genetic analysis to investigate this further.
7 Investigating Early Medieval Dietary Differences

In this chapter I address the research questions and aims tied to diet and cultural shifts during the Early Medieval period in England, taking account of the environmental variation explored in Chapter 5. These questions are:

- How does diet in England compare to the rest of western Europe in the Early Middle Ages?
- Can we see differences in childhood versus adult diet in Early Medieval England?
- Are there any sex or gender-based differences in diet?
- Do social status (from grave assemblages) and changing burial practices in Early Medieval England align with dietary change?
- Can we see the Fish Event Horizon in human tissues?
- Does diet change in England across the first millennium AD and if so when and how?

This chapter follows the same statistical procedures as Chapter 6, to contextualise England within contemporary western Europe and look at diachronic dietary shifts. I compare patterns across geo-political regions in Europe for both bone and dentine collagen and use hierarchical clustering for both tissues to categorise dietary patterns in adulthood and childhood. There are two different chemical elements (and their isotopes) from three different human tissues considered in this chapter – carbon and nitrogen from bone and dentinal collagen, as well as carbon from enamel carbonate.

Analyses are also undertaken at an England-wide scale, and the implications of the hierarchical clusters considered for English diet. I then investigate links between diet, social status and funerary change, changes across the life course, sex-based differences, offsets between tissues and whole diet, and finally look at chronological change across the first millennium AD.

7.1 Dietary differences in Early Medieval Europe

The regional and environmental differences explored in Chapter 5 highlighted some key large-scale dietary differences in Early Medieval Europe. The majority of individuals in these meta-analyses have C3 diets with a variety of protein proportions
and sources consumed from terrestrial and aquatic ecosystems. These diets appear to be relatively consistent across both bone and dentine. There are some regions where C₄/marine diets are more prominent (e.g. the eastern Mediterranean and Iberia, and northern parts of Scandinavia). England is overwhelmingly C₃ in its dietary signatures with only a small number of candidates for potential marine consumers, however I suggest that their δ¹³C values (across all tissues) show this input might be minimal in most cases. Chapter 5 also showed that certain regions within England have δ¹⁵N values that are consistent with those found in regions of Scandinavia which may imply that the foodways of these populations were more influenced by Scandinavians than others.

Therefore, I am using the western European bone and dentine δ¹³C and δ¹⁵N datasets to undertake UML hierarchical clustering, using the same procedure as for enamel in Chapter 6. This will categorise dietary patterns in terms of similarity in stable isotope values and I can test how present different dietary patterns (e.g. the FEH, higher protein and C₄ consumption) are across geo-cultural regions. This addresses my research questions about the ubiquity of changes like the FEH in different regions, as well as how diet in Early Medieval England compares to the rest of western Europe in the first millennium AD.

7.1.1 Hierarchical clustering for human bone – carbon and nitrogen

The largest dataset in this thesis is bone δ¹³C and δ¹⁵N data with 4139 entries with matched carbon and nitrogen isotope values suitable to use in hierarchical clustering. The hierarchical clustering of bone values shows two main branches (1 and 2), with branch 2 producing two distinct subclusters (2.1 and 2.2); this structure has the most support from validation indices (Appendix F). The hierarchical structure and isotopic ranges for each cluster are shown in Figure 7-1 below and visualised as a scatterplot in Figure 7-2.

Cluster 1 represents the majority of the data (n=2917) and consumers of C₃ based diets occupying a range of trophic levels. Cluster 2.1 is the smallest (n=281) and is distinguished from the others by higher δ¹⁵N values. There is some overlap in δ¹⁵N values between the three clusters but as seen in Figure 7-2, 2.1 is spatially
distinctive and I classify it as the cluster with people who have the highest terrestrial protein intake as well as marine protein consumers due to the high δ\textsuperscript{15}N\textsubscript{coll} values. Cluster 2.2 (n=941) is distinguished by its less negative δ\textsuperscript{13}C\textsubscript{coll} values and therefore includes individuals with C\textsubscript{4}/marine input but not the highest δ\textsuperscript{15}N\textsubscript{coll} values. Further subclusters in the hierarchical structure may, with more data and supervised machine learning techniques, further distinguish between trophic levels. For example, the two clear subgroups in cluster 2.2 broadly correspond to higher and lower δ\textsuperscript{15}N\textsubscript{coll} values.

Individuals in the centre of Figure 7-2 were assigned to cluster 1 and cluster 2.2 with little distance between some points, this indicates that the UML approach may have mis-assigned people, and some 2.2 cluster members might be better described by the C\textsubscript{3} dietary signatures of cluster 1. This can definitely be improved upon with more complex supervised techniques in the future, but a point of note is the similarity between this “bite” shape in Figure 7-2 and its similarity with the same shape made by the England bone data in Figure 5-9. I think that the algorithm has detected these geographical groupings and subtle similarities in the isotopic signatures despite no contextual data being used in the hierarchical clustering algorithm. This is promising for interpretation of borderline δ\textsuperscript{13}C\textsubscript{coll} values which could be caused by a variety of dietary inputs such as mixing C\textsubscript{3} and C\textsubscript{4} plant foods but may need supervised refinement for use in more complex models in the future.
Figure 7-1: Ward’s method hierarchical clustering dendrogram of Early Medieval human bone stable isotope values – with $\delta^{13}$C$_{coll}$ and $\delta^{15}$N$_{coll}$ from the same individuals (n=4139).

Figure 7-2: Scatterplot of $\delta^{13}$C$_{coll}$ and $\delta^{15}$N$_{coll}$ from Early Medieval European human bone coloured by cluster number determined by analyses from Figure 7-1.
Figure 7-3: Proportion of individuals in each bone $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ cluster coloured by region.

Figure 7-4: 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 Figure 7-1 and Figure 7-2.

The proportional distribution of bone isotopic clusters in Figure 7-3 and Figure 7-4 support my observations from Chapter 5 of a north-south gradient in diets across Early Medieval western Europe. The dominance of certain regions and areas within these clusters may be useful for human provenancing by foodways, and suggests
where some of these foodways, marine food consumption in particular, originated from.

Cluster 1 is dominated by burials in England (1899/2917) and is present in all regions except Croatia (Figure 7-4). Cluster 1 is particularly dominant in “Germanic” areas on continental Europe, and in Britain and Ireland. The North Atlantic islands and Greece also have over 50% of their analysed individuals assigned to cluster 1 showing the dominance of C₃ diets in these regions.

Cluster 2.1 contains individuals at higher trophic positions (and therefore includes some possible marine consuming individuals). Figure 7-3 shows cluster 2.1 is dominated by data from Fennoscandian regions which supports this area as the geo-cultural genesis of the FEH (Barrett, 2016; Barrett et al., 2004a; Barrett and Richards, 2004). This cluster is the most dominant in Atlantic and Arctic Norway, the Baltic, and Scotland and the Scottish Islands but is not present in high numbers elsewhere (Figure 7-4). The lack of individuals assigned to cluster 2.1 in some regions may be due to lack of access to marine resources inland. However, as many of the individuals in cluster 2.1 have bone δ¹³C_coll values below -18.5‰, perhaps these higher δ¹⁵N_coll values are better interpreted as a MEH (meat event horizon) and not solely a marine based watershed. As discussed in Chapters 5 and 6, there is evidence for freshwater fish consumption from enamel δ¹³C_carb. This is balanced with more terrestrial animal protein reliant diets. I believe cluster 2.1 with its higher δ¹⁵N_coll bone values cannot support a ubiquitous marine-based FEH across Early Medieval Europe, but instead may show increased meat consumption more broadly, and possibly even a FEH with a greater freshwater component that was near-invisible in human isotopic values previously.

Cluster 2.2 is dominated by individuals from the Mediterranean and parts of central and eastern Europe. As mentioned above, I believe the reasons for this are three-fold. Firstly, it shows the introduction of millet and other C₄ crops into Europe from the east (Amorim et al., 2018; Hakenbeck et al., 2017; Lightfoot et al., 2015; Vidal-Ronchas et al., 2019). Secondly it shows interactions across the Mediterranean into Africa and the introduction of C₄ plants through Iberia and the Balearic Islands, through late Roman and Islamic Caliphate influences (Alaica et al., 2019; Alexander et
al., 2015, 2019; Ciaffi et al., 2015; Dury et al., 2019; García-Collado et al., 2019; Gude et al., 2017; Inskip et al., 2018; Jordana et al., 2019; López-Costas and Müldner, 2016; Salazar-García et al., 2016; Saragoça et al., 2016). Thirdly it also represents individuals who are exploiting lower trophic level marine resources or eating smaller proportions of marine resources compared with those in cluster 2.1 (Bourbou et al., 2011; Bourbou and Richards, 2007; Dury et al., 2019). It can of course include individuals with any mixtures of these foodways with C₃ resources to different degrees.

There are geographical watersheds where clusters 2.1 and 2.2 dip below 50% of the sample; these are Scotland and the Scottish Isles, and Austro-Hungary and Bavaria respectively. These resource/foodways boundaries match with historical and archaeological evidence which show these regions to be key points of contact with the Viking and Hunnic groups who are credited with introducing the FEH and millet respectively (Amorim et al., 2018; Barrett et al., 2004a; Barrett and Richards, 2004; Hakenbeck et al., 2017; Richards et al., 2006; Vidal-Ronchas et al., 2019).

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 (in the bone dataset only Iceland), which is not fully understood but appears to be due to more terrestrial and freshwater resources being consumed as determined through δ³⁴S analyses (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 sign of influence from central Asian millet consumption, but instead are more terrestrially based on local C₃ resources and marine resources (Bourbou et al., 2011; Bourbou and Richards, 2007). Croatia is the only region where all individuals fell into one cluster (2.2). As I mentioned above, the algorithm included many of the individuals from Croatia with signatures more consistent with C₃ diets in cluster 2.2, perhaps reflecting the tight similarities in this and neighbouring populations, and I feel, reflecting a gradient of C₄ consumption in the bone perhaps diluted by C₃ consumption.

Returning to my central focus – Early Medieval England – hierarchical clustering of bone isotopic values confirms the dominance of foods from C₃ ecosystems. England’s cluster profile (Figure 7-4) is most similar to the Skagerrak-Kattegat-Jutland Basin,
Frisia and Saxony, and Normandy/Neustria. These regions are near neighbours with climatic and environmental similarities highlighted in Chapter 5. These regions have historically and isotopically attested migration into England during our period (see Chapter 6). There is also migration into these regions from Norway, Sweden and the Baltic (also Chapter 6). Therefore, given environmental similarities and migration between these regions, these dietary profiles make sense. Furthermore, when individuals assigned to clusters 2.1 and 2.2 are investigated in the bone collagen 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 have strong Christian ties (i.e. monasteries/churchyard cemeteries, e.g. Caister-by-Yarmouth and Raunds Furnells). These individuals represent a dual aspect to this FEH/MEH in England – introduced Scandinavian marine consumption as per the original FEH hypothesis and Christian foodways where fish were important symbolically and as a replacement for meat while fasting (Banham, 2004: 63–70; Barrett, 2003; Barrett et al., 2004a; Hagen, 2006: 393–408; Knapp, 2018).

Individuals from England in cluster 2.2 are more complex in their interpretation but are predominantly from cemeteries which span the third to fifth centuries AD and are therefore more late-Roman than Early Medieval, and as such represent different foodways. Twenty-two of the 69 individuals in England assigned to cluster 2.2 date to the later part of our period, spanning the seventh to thirteenth centuries. Most are from the churchyards in Norwich, and the Viking mass grave at Repton (Bayliss et al., 2009; Jarman et al., 2018). I therefore place these individuals into the category of marine consumers who are at a lower trophic position compared to those in cluster 2.1; they might have a high proportion of C3 resources in their diets, which reflects both Scandinavian and Christian foodways.
7.1.2 Hierarchical clustering for human dentine – carbon and nitrogen

I applied the same UML hierarchical cluster analysis to human dentine values to see how dietary signatures from childhood/earlier life diet compared with those for bone, representing later life, above. It also allows me to better assess similarities and differences between earlier life diet in England and its European neighbours. As mentioned in Chapter 5, there are far fewer Early Medieval IA studies which use dentine, so the sample size is far smaller than that for bone (n=931). The dendrogram structure for dentine is very similar to that for bone above, with two major branches in the data. Twelve cluster validation indices supported k=3 (Appendix F). The hierarchical structure of the dentine data and isotopic ranges for each cluster are shown in Figure 7-5 and visualised as a scatterplot in Figure 7-6.

Figure 7-5: Ward’s method hierarchical clustering dendrogram of Early Medieval human dentine stable isotope values – with $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$ from the same individuals (n=931).
Cluster 1 is the largest (n=552); it corresponds with bone cluster 1 and represents C₃ based diets across several trophic levels. Dentine cluster 2.1 roughly equates to cluster 2.2 in bone, and likewise has the smallest sample size for dentine (n=34). Dentine cluster 2.1 is presumed here to represent C₄/marine based diets with a similar range in δ¹⁵N values to cluster 1. Dentine cluster 2.2 is therefore marked out by its higher δ¹⁵N values compared to the other two clusters and equates to bone cluster 2.1. As with bone, individuals in this higher trophic level group mostly appear to be C₃ terrestrial or freshwater protein consumers, although a small number have δ¹³C values which overlap 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.
In Figure 7-7 the proportion of individuals from each region within each cluster is outlined while in Figure 7-8 shows the inverse. Once again, the dominance of England in my datasets is clear, making up the majority of both dentine cluster 1 and 2.2. Due to the reduced number of regions represented in the dentine samples here, regional diversity in clusters is not as high as for bone, and therefore clusters 1 and 2.2 look very similar in Figure 7-7. Despite this, my findings from Chapter 5 and the bone hierarchical clustering are supported by the dentine data, with the north-south/northwest-southeast dietary gradient running across Europe in both datasets.
Cluster 1 as the C₃ terrestrial/freshwater consuming cluster, although 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 almost entirely made of individuals buried in Croatia, with a handful of people from the Po Valley and Baltic. There is a difference between the dentine and bone from the Po Valley suggesting 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 Chapter 6). However, the lone individual assigned dentine cluster 2.1 in the Baltic is an outlier for the region and site (Triberga 45i (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 buried in 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 in Figure 7-4, with greater proportions of people with high trophic level diets found in Atlantic and Arctic Norway, and the Baltic. England and the Skagerrak-Kattegat-Jutland Basin once again closely resemble each other in cluster proportions. The individuals in England assigned to dentine cluster 2.2 are mostly later churchyard burials (e.g. Black Gate Newcastle) or from sites with known Viking links (Ridgeway Hill, Weymouth). There are six individuals dating to the sixth-eighth centuries AD. These burials are outliers for their cemeteries in being assigned to cluster 2.2, and this suggests they were migrants.

Of course, breastfeeding and weaning practices could play a role in these signatures. Although, as discussed in Chapter 5, the similarities in values and the large-scale geographical patterns seen above suggest this has minimal impact on the overall results, and that for most regions childhood and adult diets were very similar.
Recap of main findings:

- Clear north-south gradient across Europe in diets found in both bone and dentine from high trophic level diets to lower trophic level C₄/marine diets.
- Majority of western Europe consumed C₃ based diets in both childhood and adulthood.
- Childhood and adulthood diets appear similar in most regions, with the exception of the Po Valley.
- England most closely resembles the Skagerrak-Kattegat-Jutland Basin, Frisia and Saxony, and Normandy/Neustria in terms of diet cluster patterning which matches the similarities in ecology of these regions and migrant histories.
- Clear evidence for increased trophic level diets over time in England linked to Vikings and Christian foodways, but not necessarily a straightforward FEH.

7.2 Dietary change over time in England – burial, life course, sex, & chronology

This section investigates the relationships between biological and cultural variables and dietary stable isotopes in Early Medieval England. I address here the overarching research question of if and how major socio-environmental transitions in the first millennium AD impact on foodways as measured by isotopic data. The emphasis here is on the cultural changes during the first millennium AD and their role in diet, but climate change is also considered.

7.2.1 Social status, shifting burial practices and diet

Social status and hierarchy has largely been the realm of historians and funerary archaeologists due to the elite nature of texts and varied grave provisioning in cemeteries respectively. Assumptions around wealth and social status, and the number and kinds of grave goods are readily made; and certain styles of female dress accessories are often taken to be ethnic signifiers (Geake, 1995; Lucy, 2000; O’Brien, 1999; Owen-Crocker, 2010; Walton Rogers, 2014). Early Medieval social structure in England, at least in the earlier centuries, relied on kingship via divine descent and strong kinship ties were paramount for law and order (Adams, 1901; Brown, 1973; John, 1963; Lancaster, 1958a, 1958b; Loyn, 1974; Stenton, 1971: 277–318). The earliest law texts from Kent (c. 602) and Wessex (688-694) show that there was a
nobility below the royals but the majority of society were free peasants who answered only to the king; however, from the conversion period onwards these social structures became mutable, which is echoed in the funerary archaeology (Brownlee, 2019; Buckberry, 2007; Craig-Atkins, 2017; Geake, 1995; Lambert, 2017; Lucy, 2000; Richards, 2015; Whitelock, 1979, 1996). Work on Early Medieval agriculture and food has shown that types and quality of food and drink varied with social status (Banham, 2004: 71–76; Frantzen, 2014: 34–80; Hagen, 2006: 451–462; Knapp, 2018; Lee, 2013).

I investigated links between diet, social status and funerary orthopraxy by looking for correlations with a variety of funerary variables (number of grave goods, number of foreign grave goods, body position and grave orientation) and bone δ¹³C_coll and δ¹⁵N_coll values. Some funerary variables were not analysed here but are included in the database. For instance, internment style had too many variants that are not easily standardised for visualisation or statistical analyses. Number of grave goods is a rough measure of wealth and status, so too are the number of foreign grave goods (Geake, 1995; King, 2004; Lucy, 2000). Grave orientation becomes standardised over time with Christian burial rites, so differences in diet and possible religious change are tentatively investigated through this and body position (Brownlee, 2019, 2020; James, 1989; Leggett, 2014; Longley, 2002; Mui, 2018). Since burial practices change throughout the first millennium AD, points have also been coloured by broad period.

The resulting plots can be found in Appendix J with Figure 7-9 below as an example. None of the analyses showed any clear relationships between funerary practices, social status and diet. Some chronological differences are however visible where more than one time period is present for a funerary variable. This suggests that social status and wealth as judged by grave goods does not correlate with significantly higher protein consumption or eating different resources such as fish, in the periods where furnished burial was still the norm (e.g. Figure 7-9). This supports my interpretation that the major driving forces behind any change in diet in England during the first millennium AD are more complex than a straightforward FEH and therefore do not correlate with any one aspect of burial practice.
In all five figures (Appendix J) the majority of “unknown/NA individuals” and the commingled and mass grave burials are potential Scandinavians, as identified by the original investigators, with bone cluster 2.1 and 2.2 signatures (Chenery et al., 2014; Loe, 2014; Pollard et al., 2012). This suggests that diets in England were not changed by the FEH in the Early Middles Ages, but FEH signatures in the region are the result of incoming people.

The well-known changes in burial practice from the end of the Roman period to churchyard burials in the eighth/ninth centuries are clearly shown in this smaller subset of burials with stable isotope data (Brownlee, 2019; Geake, 1995, 2002, 2003; Leggett, 2014; Lucy, 2000). It supports and expands the findings of Hannah and Hull that there is no link between social identity/status and dietary isotopes for this period, but contradicts the smaller scale correlations seen at sites such as Berinsfield, because sample sizes are usually too small and researchers often actively hunt for variation (Hannah, 2015; Hannah et al., 2018; Hull, 2007; O’Connell and Hull, 2011; Privat et al., 2002). I suggest that the social hierarchy seen in Early Medieval cemeteries and the foodways of these communities may be biochemically ephemeral, played out through politics, material culture and specific kinds of food (e.g. special cuts or types of animal, fruits etc.) rather than an increased amount of protein or environmentally different resources (e.g. marine foods) that would show up in
isotopic data. There is some zooarchaeological evidence from high status sites of marine fish (Bishopstone and Lyminge) which will be discussed more in Chapter 8 as part of the case studies, which it is believed are linked to the Christianisation of these sites, as well as their higher social status (in the case of Lyminge moving from great hall complex to a minster) (Knapp, 2018; Thomas, 2010, 2013; Thomas and Knox, 2012). However, the decline of furnished burial from this period when marine fish are becoming more prominent at these sites (c. late seventh and eighth centuries) and the supposed calendarized eating of fish for Christian feast days (meaning the marine protein input would be overall minimal and swamped by other signatures in tissue formation if not eaten regularly), alongside a lack of burials clearly associated with such settlements makes it nearly impossible to link burial practice, social status and diet for such sites as demonstrated above (Banham, 2004; Hagen, 2006; Knapp, 2018; Reynolds, 2015; Whitelock, 1994).

Recap of main findings:

- No clear link between burial practices or indications of wealth/social status and dietary stable isotopes.
- The chronological aspect in both diet and changes in burial practices is clear with both changing through time, however number of grave goods, body position, and grave orientation do not align with isotopic shifts.

7.2.2 Changes through the life course

Written sources suggest that, beyond breastfeeding, infants and children had different diets to adults in Early Medieval England (Hagen, 2006: 425–427, 445–446). Young children and infants supposedly had dairy and cereal heavy diets, with paps, porridges and bread (soaked in milk or with cheese) suggested for the young. Children were also allowed to drink ale but not wine as ‘wine is not the drink for children or the foolish’ (Aelfric, n.d.; Hagen, 2006: 426). Funerary provision in Early Medieval England also appears to mark clear life stages with gendered grave goods being assigned to children and adults (or in some cases taken away) at stages such as puberty or menopause (Grove and Lancy, 2018; Stoodley, 1999, 2000, 2011). These stages were used in Chapter 3 to assign individuals to gendered age categories and life stages which are used here.
This section therefore asks if there are differences between childhood and adult diet in Early Medieval England and if so, do these relate to age categories and rites of passage? This is tackled first by comparing lifetime dietary averages (from bone) across age categories, and then by using a multi-tissue approach (bone versus dentine) to look at changes during the life course. As per tissue formation timings and fractionation principles mentioned in Chapter 2, dentinal collagen reflects protein consumption during the formation of the tooth root and does not substantially remodel during life, giving a time constrained dietary snapshot. Bone collagen also reflects predominantly dietary protein but is a longer-term average over several years of bone formation and remodelling, dependent on the skeletal element in question. This allows me to compare dietary protein through the life course on individual and population scales.

I start by looking at gendered age at death categories and bone $\delta^{13}$C$_{\text{coll}}$ and $\delta^{15}$N$_{\text{coll}}$ values. These are based on Stoodley’s (1999, 2000, 2011) gendered rites of passage at different ages determined from grave assemblages (see Chapter 3). This was done to discern if dietary patterns in bone differ between cultural age categories. I then compare dentine and bone values to see if there are overall patterns in childhood versus adult diet.

The relationship between height and dietary stable isotopes as a way to look at diet and health was also explored through simple linear regression analyses, but no relationships were found, and further investigation was outside the scope of this thesis. For details see Appendix II.

7.2.2.1 Age categories
I assessed bone $\delta^{13}$C$_{\text{coll}}$ and $\delta^{15}$N$_{\text{coll}}$ values by the age categories set out in Chapter 3 (Table 3-2). To summarise: age categories 0-2 are non-gendered and represent infants and children up to ~10 years old. Age categories 3+ are gendered by grave goods where these are present in earlier cemeteries and based on osteological sex for unfurnished churchyard cemeteries. There are also unsexed/ungendered age categories for earlier graves with a lack of either/both lines of evidence. In brief, age
category 3 are “teenagers”, 4 are aged ~18+, 5 approx. 30+ and 6 are the oldest individuals.

For ease of interpretation these categories were combined and simplified into larger groups for visualisation in Figure 7-10, Figure 7-11, Figure 7-12 and Figure 7-13 below (for analysis of raw age categories see Appendix I). I combined children and infants without gendered grave goods into the “child” category and kept the ambiguous “juvenile” and “adult” categories as per Table 3-2. I then grouped gendered and un-gendered individuals into life stages 1-3, 3-5 and 5-6 to show progression from infancy/childhood, to early adulthood, and through middle and later adult life stages.

Child and “NA” individuals have slight $^{13}$C enrichment, but overall all age categories align in their central tendencies close to the average in England of -20‰ which supports my earlier observations above of very little difference in bone $\delta^{13}$C values across England.

*Figure 7-10: Ridge plot of bone $\delta^{13}$C values from England by simplified gendered age categories (see Chapter 3 for age ranges).*
Similarly, for bone $\delta^{15}$N$_{coll}$ values children show isotopic enrichment (mean=10.8‰) compared to “juveniles” and older age categories who have means between 9-10‰. This enrichment is small and could be due to a variety of factors already discussed above and in Chapter 5, including breastfeeding and physiological stress.
These overall similarities in distribution shapes, ranges and central tendencies across all age categories show that there are no isotopic differences between stages of the life course for either males or females that align with either major biological or cultural rites of passage. Diets of children and adults could have been different in other ways which are not visible using IA. It also suggests that there may be no gendered or sex-based differences in diet which are visible isotopically.

7.2.2.2 Bone versus dentine and survivorship

Despite the remarkably similar results from the comparison of bone between different age groups above, using isotopic values from bones of deceased children as a signature of “average” Early Medieval childhood diet is obviously problematic and raises issues surrounding the osteological paradox (DeWitte and Stojanowski, 2015; Siek, 2013). Therefore, comparisons between tissues of individuals who have survived into adulthood are better for life course comparisons. I produced a series of bag plots to investigate the impact of the osteological paradox and survivorship and to compare dietary signatures from both tissues with and without deceased juveniles included, as well as plots with data from the same individual (Figure 7-14).
For individuals with more than one bone sampled (e.g., Westfield Farm Ely), the rib was preferentially selected here (due to it representing the diet closest to the end of life; see Chapters 2-4). For individuals with incremental dentine, the average of these samples was used to compare with the majority of samples which are bulk (e.g., Raunds Furnells). For individuals with multiple teeth sampled for either enamel (for later analyses) or dentine (or both), permanent M2 or PM2s (dentine representing diet from approx. 6-14/7-16 years of age) were selected to conform with my primary dataset but this was not always possible. The “Tissue Age” column in the dentine spreadsheet (see Digital Appendix) indicates that for England before excluding juveniles or individuals with only one tissue present, the dataset represents diet from close to birth up to 25 years of age (see Table 2-1 for formation ages for each tooth), and these age window differences are highlighted in Figure 7-14 below.
Figure 7-14: Bag plots of bone versus dentine $\delta^{13}{\text{C}}_{\text{coll}}$ and $\delta^{15}{\text{N}}_{\text{coll}}$ in Early Medieval England. a) all data in England for both tissues and all age categories (bone n=2019, dentine n=735), b) with individuals under age category 3 removed for both tissues (bone n=1761, dentine n=466), c) all age categories but only those with matched bone and dentine from the same individual (n=300), d) individuals with matched bone and dentine with individuals below age category 3 and below removed (n=273).
Figure 7-14 shows the impact of survivorship and of non-matched values. The main point I want to highlight is that from a) through to d) the degree of overlap in the bags and loops of the plots increases and there is an increasing similarity in shape. This means that for matched individuals who survived childhood mortality, diet through the life course is virtually the same. This is supported by BEST tests (Appendix D). It also shows that the osteological paradox, especially when it comes to understanding trends in infant and child data, or when using dead children to represent the life course, can have large implications for dietary IA research. Individuals who do not survive childhood have different isotopic signatures, especially in their dentine values which reflect breastfeeding and the degree of stress their bodies were under during their short lives (Beaumont et al., 2015, 2018; Julia Beaumont et al., 2013; Beaumont and Montgomery, 2016; Crowder et al., 2019; Fuller et al., 2005; Haydock et al., 2013; Swales, 2012). This is as true in Early Medieval England as in any other population.

The differences in shape between a) and b) above highlight that dentine from the Raunds infants really heavily dictates the shape and range of the dentine dataset and may lead to false interpretations of the data. The additional infant and child dentine included in Figure 7-14 a) but not in b) shows greater $^{15}$N enrichment, which, as I have already mentioned, could be the result of breastfeeding and/or physiological and nutritional stress. This agrees with the original research findings (Beaumont et al., 2015, 2018; Fuller et al., 2005; Haydock et al., 2013). There are some changes in the shape of the bone bag plot between a) and b) and between b), and c) and d) which are similar with only minor differences between these last two bag plots.

Another interesting finding from Figure 7-14 is that the bags and loops for dentine, even in matched individuals, are larger than those for bone. I believe this is due to some breastfeeding signatures possibly being in the dataset, as well as the physiological differences between these two tissues – the period of diet each represents and bone turnover, and differences in isotope portioning and fractionation between bone and dentine. However, as the BEST tests show (Appendix D), these differences are negligible and are less than trophic level enrichment and, in many cases, smaller than analytical error.
Recap of main findings:

- Survivorship has a large impact on dietary isotope patterns, especially dentine $\delta^{15}N_{\text{coll}}$ values.
- No evidence to suggest isotopically different diets through the life course in Early Medieval England.
- For those who died in adulthood, diet remained the same through life.

7.2.3 Sex based differences in diet

Female funerary displays in the sixth to late seventh century AD are often more elaborate than males, with the exception of “princely” burials like Sutton Hoo mound 1 and Prittlewell (Carver, 1992; Hamerow, 2016; Hamerow et al., 2015; Hirst et al., 2004; Lucy, 2000, 2011; Lucy et al., 2009; Stoodley, 1999). In the seventh century there is also the fascinatingly brief emergence of “bed burials” as a high status female funerary rite, with four of these women part of this analysis (C Evans et al., 2018; Lucy, 2016; Malim and Hines, 1998; Penn, 2011). These elaborate funerary displays compared with the relative paucity of textual sources about Early Medieval women in England (of any rank) raises questions around their role in society and politics (Bitel, 2002; Fell, 1986; Gilchrist, 1994; Hamerow, 2016; Lucy, 2011; Stoodley, 1999). Fell (1986) was the first to paint a picture of Early Medieval England as a society where women had many legal rights, as well as political and religious power; however, they were not fully equal in social or legal status to men. For non-elites the assumption is that domestic tasks, especially those around cooking and food preparation happened predominantly in the female sphere and that women bore the brunt of food shortages, so perhaps diet (and therefore isotopic values) could differ with gender roles (Banham, 2004: 18, 54, 56; Hagen, 2006: 248, 255, 261, 263, 280–81, 452). Male feasting is heavily emphasised in the secular texts of the time, which might suggest higher protein consumption ($^{15}$N enrichment) in men (Banham, 2004: 71–77; Frantzen, 2014: 34–58; Hagen, 2006: 411–427). There is also some evidence that physiological differences between females and males can cause differences their dietary stable isotopes, especially if a woman is pregnant or breastfeeding (Beaumont et al., 2015; Fuller et al., 2005, 2006; Reitsema and Vercellotti, 2012; Vercellotti et al., 2011; Vidal-Ronchas et al., 2019).
Despite these cultural and biological differences between the sexes and gender roles, I found no differences in diet between the gendered age groups in section 7.2.2.1. Although gender and biological sex are tightly enmeshed in Early Medieval England, I have analysed osteological sex here as they are not mutually exclusive, and to better assess impacts of physiology on dietary isotope fractionation. The results can be seen here in Figure 7-15 and Figure 7-16.

Figure 7-15: Violin plots of Early Medieval bone $\delta^{13}C_{coll}$ values from England by broad date category and osteological sex.

Figure 7-16: Violin plots of Early Medieval bone $\delta^{15}N_{coll}$ values from England by broad date category and osteological sex.

When visually assessed there are no large differences between female or male diets in bone $\delta^{13}C_{coll}$ or $\delta^{15}N_{coll}$ values in any of the three periods. As in the previous chapters, variation in un-sexed individuals was ignored due to the large degree of biological uncertainty. There are some chronological changes, which will be explored more below.
BEST tests were performed on bone and dentinal collagen, and enamel carbonate data to test the strength of my visual observations of no clear sex-based isotopic differences (see Appendix D). The PPD (posterior predictive distribution) means for $\delta^{13}C_{coll}$ are very similar across all periods, with a consistent offset of 0.1‰ between sexes. This is below machine error (0.2‰) so may not be biologically meaningful. There are slight increases visible for $\delta^{15}N_{coll}$ PPD values through time for both sexes, and males have consistently higher $\delta^{15}N_{coll}$ values in all periods. For both bone $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$, the tests between sexes for the overall time span and Early Medieval sub-period did not span zero, indicating there might be a real difference between group means. These differences could be indicative of physiological or dietary differences between the sexes. However, the MDMs (mean of the difference of the means) in all eight tests were less than 1‰, and in most cases less than machine error, so I conclude here that there are no major isotopic differences in female and male diets as reflected in bone collagen. This means that we can combine the sexes for chronological analyses below.

The results from BEST tests on enamel $\delta^{13}C_{carb}$ values show no differences between females and males overall or within each period, with all three tests spanning zero and small MDStdev and MDM scores (Appendix D). So, as above the sexes will be combined for chronological analyses.

For dentine collagen, the models did not converge for the Roman period due to small sample sizes for both sexes (F=3, M=5) so no further interpretation of the results are made here. Otherwise, results are similar to those seen above for bone collagen, with relatively consistent $\delta^{13}C_{coll}$ values over time, and a slight increase in $\delta^{15}N_{coll}$ chronologically in both sexes. There are offsets in $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ between females and males but these are less consistent than in bone. The only period to produce a MDM which does not span zero is the Viking to Anglo-Norman period for dentine $\delta^{13}C_{coll}$ with a difference of 0.62‰. This difference is above machine error but less than consumer-prey collagen differences 1.3±0.6‰ so I do not consider this a dietary/culturally significant difference between female and male stable isotope values (Bocherens and Drucker, 2003; Fox-Dobbs et al., 2007; Post, 2002; Reynard, 2017). Although with more data this may prove to be a real physiological difference.
brought about by metabolic differences between the sexes. As with bone and enamel above, childhood diet of females and males (seen here in dentine stable isotope values) are the same and will also be combined for chronological analyses.

Despite small variations, no significant differences were seen between female and male dietary stable isotopes across three tissues (bone, dentine and enamel). Small offsets between the sexes are probably due to physiology but these are too close to machine error or consumer/prey offsets to be certain. Whatever the cultural mechanisms were that resulted in gendered food roles, these are not visible in the isotopic data. There are indications above of some chronological dietary shifts, especially in $\delta^{15}N$ values (bone and dentine), so the sexes will be combined in chronological investigations below.

Recap of main findings:

- No major differences found in diet between females and males across bone, dentine and enamel in any period.
- Small systematic offsets between sexes may show physiological differences but this is often less than machine error.
- Evidence for chronological dietary changes in both sexes, especially in $\delta^{15}N$ values.

7.2.4 Whole diet and trophic level shifts

In this section I have taken an exploratory approach to compare between enamel carbonate, dentine and bone collagen more directly. I am interested to see if tissue offsets and comparisons, particularly between enamel carbonate and $\delta^{13}C_{\text{coll}}$ from dentine, can help discern freshwater resource consumption, as mentioned in Chapter 5. Following on from section 7.2.2 I consider if there is a chronological impact on dietary patterns through the life course – does chronology play a role in differences between childhood and adulthood diets?

These questions are tackled by using a multi-tissue and multi-scalar approach. Three tissues – tooth enamel ($\delta^{13}C_{\text{carb}}$), dentine and bone (both $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$) – are examined sometimes by themselves and often in comparison. As per the physiological
and biochemical principles mentioned in Chapter 2, tooth enamel carbonate reflects whole diet from the period of the crown’s development (often earlier childhood, dependent on the tooth), and is not substantially remodelled during life, giving, alongside dentine, a time constrained dietary snapshot. This allows me to compare whole diet and protein consumption through the life course on multiple scales.

First, I compare $\delta^{13}$C value distributions, and then use a series of bag plots and scatterplots to investigate dietary change across these tissues with $\Delta^{13}$C and $\Delta^{15}$N values. Some of the chronological aspects of whole diet and change through the life course will be covered here, and the rest will be touched on below in section 7.2.5.

I calculated both $\varepsilon$ and $\Delta$ values to describe isotopic differences between tissues, where $\varepsilon$ values give the “true” isotopic difference between two $\delta$ values, and $\Delta$ values give the simpler difference between them (Cerling and Harris, 1999; Clementz et al., 2009; Kusaka et al., 2015). For example:

$$
\varepsilon^{13}_{\text{enamel-dentine}} = \frac{1000 + \delta^{13}_{\text{enamel}}}{1000 + \delta^{13}_{\text{dentine}} - 1} \times 1000
$$

$$
\Delta^{13}_{\text{enamel-dentine}} = \delta^{13}_{\text{enamel}} - \delta^{13}_{\text{dentine}}
$$

These enrichment factors were compared using simple linear regressions for different tissue combinations and the differences were negligible (often less than $0.02\%$, see Appendix E.ii). Therefore, the more straightforward $\Delta$ values are reported here.
Figur 7-17: Violin plots comparing the distributions of δ¹³C in different tissues (L-R): δ¹³C_{coll bone} δ¹³C_{coll dentine}, and δ¹³C_{carb enamel} from Early Medieval England.

Since I have already demonstrated that bone and dentine are comparable in Early Medieval populations in England, offsets between enamel, bone and dentine will be extremely useful in investigating other aspects of Early Medieval diet such as lipid consumption, and freshwater and marine resource consumption in particular. Through looking at the data in terms of environment and regions, I have already found evidence for freshwater resource consumption in Chapter 5. The similarities in δ¹³C distributions shown in Figure 7-17 above are as described in Chapter 5 and for bone-dentine comparisons in section 7.2.2.2. The δ¹³C ranges for all three tissues are roughly the same (~4-7‰). The tighter modality and range of dentine may reflect its shorter formation period and lack of remodelling. Bone’s larger range therefore showcases the longer period of diet it can reflect, and variability introduced by turnover. The multimodality and more bulbous distribution shape of δ¹³C_{carb} in tooth enamel highlights the wider macronutrient pool it is formed from (carbohydrates, lipids and proteins), and the range of C₃ resources consumed in Early Medieval England which are not visible by using only δ¹³C_{coll}. There are only two individuals with δ¹³C_{carb} values above -12‰ who might have heavy (>50%) C₄/marine input in their whole diets (Clementz et al., 2007, 2009; Codron et al., 2018; Cramp et al., 2014; Kusaka, 2019; Kusaka et al., 2015). When this is visualised three-dimensionally, coloured by time period, we can see that, broadly, lower collagen δ¹³C values in bone and dentine co-occur and correspond with the lowest δ¹³C_{carb} values (Figure 7-18). What is also evident here is that there do not appear to be any differences between c.350-790AD and c.790-1066+AD for all three δ¹³C values in the same individuals. These chronological patterns will be discussed more in depth below in section 7.2.5.
As suggested by the ecological data in Chapter 5 I see correlations between bioapatite and collagen which support varied diets in England ranging from more freshwater-based to perhaps a small amount of marine intake, which is more prominent in Figure 7-18 than in Chapter 5 (Clementz et al., 2007, 2009). To better distinguish the relationships between tissues and what this means for Early Medieval diet in terms of aquatic resources, I used Δ values as described above for $\Delta^{13}C_{\text{enamel-dentine}}$, $\Delta^{13}C_{\text{dentine-bone}}$ and $\Delta^{15}N_{\text{dentine-bone}}$, plotting these together and against δ values in various combinations seen in Figure 7-20 and Figure 7-21 below as bagplots, and Figure 7-22 and Figure 7-19 as 3D scatterplots. For $\Delta^{13}C_{\text{bioapatite-collagen}}$ (here enamel-dentine), 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). $\Delta^{13}C_{\text{bioapatite-collagen}}$ 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 et al., 2007, 2009; Clementz and Koch, 2001; Kusaka et al., 2015). Therefore $\Delta^{13}C_{\text{bioapatite-collagen}}$ values coupled with other measures from bone and dentine can help disentangle protein source exploitation in Early Medieval England.

Tissue offsets are however not straightforward, especially in omnivores (i.e. humans). A recent feeding study on pigs suggests that the introduction of marine resources into the diet can substantially change nutrient pooling and dietary routing of amino acids and thus change the $\Delta^{13}C_{\text{whole diet-tissue}}$ relationship that holds well in terrestrial contexts (Webb et al., 2017). However, Webb et al. (2017) did not collect enamel carbonate samples in their study, so it is hard to interpret how this plays out in bioapatite versus proteinaceous tissues (collagen) to attempt corrections and better understand the whole diet-apatite relationship in omnivores. Kellner and Schoeninger (2007) demonstrate how useful plotting $\delta^{13}C_{\text{coll}}$ versus $\delta^{13}C_{\text{apatite}}$ is for disentangling C3, marine and C4 protein consumption (but did not consider freshwater fish in any detail in their models). Their inferences are made harder to apply here to England as many of the archaeological populations they were investigating had some C4 intake, which is the case for most human enamel $\delta^{13}C$ studies which were used to construct these interpretive models (Kellner and Schoeninger, 2007; Lee-Thorp et al., 1989; Loftus and Sealy, 2012). Although their
work does suggest that $\Delta^{13}$C_{bioapatite-collagen} values in humans (and other animals) may not always reflect trophic level (Webb et al., 2017). Looking at a combination of the ecological literature and work done on Jomon period Japanese populations (discussed above), alongside the discussion above of populations in Norway in Chapter 5, suggests that $\Delta^{13}$C_{bioapatite-collagen} values can give a suggestion of trophic-like relationships, in particular for disentangling proportions of mixed marine/terrestrial/freshwater protein discrimination (especially in otherwise C$_3$ environments). If marine protein is visible in collagen (given the thresholds above), but not in apatite (in $\delta^{13}$C and/or $\Delta^{13}$C_{bioapatite-collagen} values), this indicates that whilst marine resources may dominate the protein portion of the diet, the bulk of other aspects of diet (lipids, carbohydrates etc.) and thus the majority of dietary energy is drawn from terrestrial resources, and possibly reflects lower trophic level consumption of these non-marine resources, and conversely where there is little to no marine or C$_4$ input $\Delta^{13}$C_{bioapatite-collagen} values may be used more reliably as indicators of freshwater/terrestrial input. Although caution is needed as more feeding studies and work on modern populations (both animals and people) is needed to better understand underlying dietary routing and isotopic composition of all portions of foodstuffs.

I first quantify the degree of change in diet over the life course and chronologically using $\Delta$ values. In Figure 7-19 it is clear that $\Delta$ values for dentine-bone differences reinforce my previous conclusions of little difference across the life course since values cluster around zero. There are larger differences evident between enamel and dentine which help elucidate trophic levels further. There is no clear chronological trend here in any of the tissue offsets, which we might expect to see on the $\Delta^{13}$C$_{enamel-dentine}$ axis if there was indeed a FEH (more individuals closer to $\sim$4‰ despite little change over life course from c.790-1066+AD).
Figure 7-18: Scatterplots of human $\delta^{13}$C<sub>carb</sub>, $\delta^{13}$C<sub>bone</sub>, and $\delta^{13}$C<sub>dentine</sub>, coloured by time period – a) 3D scatterplot, b) $\delta^{13}$C<sub>bone</sub> and $\delta^{13}$C<sub>carb</sub>, c) $\delta^{13}$C<sub>bone</sub> and $\delta^{13}$C<sub>dentine</sub>, d) $\delta^{13}$C<sub>dentine</sub> and $\delta^{13}$C<sub>carb</sub>.
Figure 7-19: Scatterplot of human $\Delta^{15}N_{dentine-bone}$, $\Delta^{13}C_{dentine-bone}$, and $\Delta^{13}C_{enamel-dentine}$, coloured by time period; a) 3D scatterplot, b) $\Delta^{13}C_{dentine-bone}$ and $\Delta^{15}N_{dentine-bone}$, c) $\Delta^{13}C_{dentine-bone}$ and $\Delta^{13}C_{enamel-dentine}$, d) $\Delta^{13}C_{enamel-dentine}$ and $\Delta^{15}N_{dentine-bone}$. 
Figure 7-20: Bag plots comparing tissues through enrichment factors in Early Medieval England from individuals with matched tissue IA data. a) $\Delta^{13}C_{\text{dentine}}$-bone and $\Delta^{13}C_{\text{dentine}}$-bone b) $\delta^{15}N_{\text{dentine}}$ c) $\delta^{15}N_{\text{dentine}}$-bone and $\delta^{13}C_{\text{dentine}}$-bone d) $\delta^{13}C_{\text{bone}}$-coll and $\Delta^{13}C_{\text{dentine}}$. 
There are no strong trends visible Figure 7-20 either. Figure 7-20 a) shows differences between bone and dentine carbon and nitrogen isotope ratios. These are tightly clustered around zero, with a slight trend towards the bottom left corner which indicates some individuals have increasing protein consumption over their life course. This further supports my conclusions of no major dietary changes between the periods represented by dentine and bone. Chronology is investigated further below.

Figure 7-20 b) looks at $\Delta^{13}C_{\text{enamel-dentine}}$ versus $\delta^{15}N_{\text{dentine col}}$ to assess protein source consumption as per Clementz et al. (2009) and Kusaka et al. (2015). I would expect to see a stronger linear-like relationship from the top-left corner to the bottom-right if there was any significant marine protein consumption in Early Medieval populations in England, as was the case for Jomon period people in Japan (Kusaka et al., 2015). There is a slight diagonal shape to the bag plot, but this is not strong enough to suggest any considerable marine resource exploitation in either protein or whole diet.

Figure 7-20 c) compares $\Delta^{13}C_{\text{enamel-dentine}}$ and $\Delta^{13}C_{\text{dentine-bone}}$. This confirms the lack of any significant $C_3/C_4$ shift in diet with $\Delta^{13}C_{\text{dentine-bone}}$ values never going beyond ±1‰. What it highlights acutely is the large range of trophic levels occupied by Early Medieval people, as mentioned earlier. Figure 7-20 d) highlights the low variability in $\delta^{13}C_{\text{col}}$ values in England and their very strong $C_3$ signatures. Those with $\Delta^{13}C_{\text{enamel-dentine}}$ values above ~6‰ are consistent with herbivores, and those with values closer to ~4‰ are similar to North American carnivores (wolves and cougars) (Clementz et al., 2009). To compare this with the Jomon model, these combinations of $\Delta^{13}C$ and $\delta^{13}C$ values suggest dietary energy predominantly drawn from terrestrial, and possibly freshwater resources. All of these data points towards a lack of evidence for a marine FEH, although there are some potential, weak, marine trends in figures above.

So, can I get better clarity on the FEH and freshwater fish consumption? The best way to resolve this is by considering the relationship between $\delta^{13}C$ values and $\Delta^{13}C_{\text{enamel-dentine}}$. Less-negative $\delta^{13}C_{\text{col}}$ values (see Chapter 1 for more details on thresholds, but the higher above -18.2‰ the higher the percentage of marine protein) are indicative
of C₄/marine consumption; and more-negative values are indicative of freshwater resources, with terrestrial resources in the middle. Similarly, less negative δ¹³C_carb values (the closer to -10‰ or above the better) are indicative of marine consumption, with freshwater resources at the other end of the spectrum and terrestrial diets in the middle. In simpler ecological model species, the lower the Δ¹³C enamel-dentine value the higher the trophic level, with wolves consuming a mixture of terrestrial animals and freshwater fish ~4‰, and toothed whales below 2‰. Marine predators would have low Δ¹³C enamel-dentine values but higher δ¹³C values for collagen and carbonate (Clementz et al., 2007, 2009). I would therefore expect people exploiting more marine resources, especially fish, to have this kind of directionality in their values, even if the relationship is not as simple (as discussed above), although not as extreme, as this is what was evident for Jomon groups exploiting marine resources (Kusaka, 2019; Kusaka et al., 2015).

In Figure 7-21 I found a very strong pattern but in the opposite direction to the marine diet gradient found by Kusaka et al. (2015) (red line). Individuals with a higher trophic level based on whole diet (rather than solely protein by using δ¹⁵N) have lower δ¹³C_carb values consistent with freshwater ecosystems (Clementz et al., 2007). People at the other end of the scale have δ¹³C_carb- Δ¹³C enamel-dentine combinations consistent with terrestrial omnivores and herbivores (Clementz et al., 2009; Kusaka et al., 2015).

Figure 7-21: Bag plot of Δ¹³C enamel-dentine and δ¹³C_carb for Early Medieval England.
Figure 7-22 takes this one step further by adding dentine $\delta^{13}C_{coll}$. The red line indicates the expected trend for increasing marine consumption. The individuals in this study do not fall along this plane and have an entirely different directionality. Based on Figure 7-22 I suggest Early Medieval diets in England lie along a gradient of terrestrial and freshwater omnivorous to more plant-based diets when compared to the ecological literature (Clementz et al., 2007, 2009; Clementz and Koch, 2001; Crowley et al., 2013; Cullen et al., 2019; Eccles et al., 2020; Franco et al., 2013; Juarez-Sanchez et al., 2019). This is supported by the environmental trends seen in Chapter 5.

The similar directionality seen in the some of the graphs above to those in Kusaka et al. (2015) whilst not indicating marine consumption, give an idea of trophic levels and sources of lipids in human diets which are “fishy” but not marine as suggested by comparison with freshwater mammals (Bearhop et al., 1999; Bliss, 2014; Clementz et al., 2007, 2009; Clementz and Koch, 2001; Guiry, 2019). Since these enrichment factors and tissues comparisons are generally used in human studies with assumed marine or C₄ consumption, there are no comparative studies in humans or model omnivores with confirmed freshwater consumption with $\delta^{13}C_{carb}$, researchers tend to use sulphur isotope data instead, although this is not widespread (Kusaka et al., 2015; Loftus and Sealy, 2012; Nehlich, 2015; Sayle et al., 2013). As such, the best proxies have been wolves who eat salmon, manatees, and river otters (Bearhop et al., 1999; Bliss, 2014; Clementz et al., 2007, 2009; Clementz and Koch, 2001; Crowley et al., 2013; Franco et al., 2013; Guiry, 2019; Juarez-Sanchez et al., 2019). More work needs to be done in this area, especially combining $\delta^{13}C_{carb}$, $\delta^{13}C_{coll}$ with $\delta^{34}S_{coll}$ in a variety of ecosystems.
Recap of main findings:

- No evidence for diachronic shifts in life course dietary change.
- Combining $\delta^{13}C_{\text{dentine coll}}$, $\delta^{13}C_{\text{carb}}$ and $\Delta^{13}C_{\text{enamel-dentine}}$ data shows no evidence for the FEH in England before the eleventh century with the data here (see Table 3-6 and Digital Appendices for chronological sample sizes and sites with matched tissues).
- There is evidence for a gradient between “herbivore” like diets and higher meat consumption from both freshwater and terrestrial resources.

7.2.5 Chronological Changes in Diet

Throughout this thesis I have found chronological trends in the isotopic data whilst investigating other variables, for both diet and mobility. It is clear that diet changed through time in Early Medieval England but how, why and when?

One of the prevailing narratives of the last two decades in the study of Early Medieval diet has been of the “Fish Event Horizon” (FEH) at the turn of the first millennium AD, increasingly strict Christian dietary laws and increased meat consumption (at least for elites) after the Norman Conquest (Barrett, 2003, 2016; Barrett et al., 2004a; Barrett and Richards, 2004; Jervis et al., 2017; Orton et al., 2017; Woolgar, 2016; Woolgar et al., 2006).
Alongside looking at chronological change in a more general sense, an aim of this thesis has been to interrogate the FEH and see if I could find it in human tissues across Early Medieval England. Müldner (2016) highlights that the chronology of cemeteries makes finding the FEH in human isotope values before the Anglo-Norman period difficult, and that East Anglia provides the best evidence for earlier marine consumption. I have also identified this trend in collagen from East Anglia, however the enamel carbonate for the region does not support this. Although, as yet, enamel carbonate values has not been analysed from Hull’s (2007, 2011) cemeteries which give the best evidence of marine consumption (i.e. Caister-by-Yarmouth and South Acre). There is also evidence for major agricultural and dietary shifts between the Roman and “Anglo-Saxon” periods as well as an agricultural “revolution” in the eighth-ninth century (Banham and Faith, 2014b, 2014c; Crabtree, 1989, 2010; Hamerow et al., 2020; Rizzetto et al., 2017). Therefore, there are many possible chronological targets and changes to foodways and agriculture during the Early Middle Ages in England. As I highlighted in Chapter 3, and Brownlee (2019) and Müldner (2016) amongst others have pointed out, getting precise dates for cemeteries and skeletons after the end of furnished burial and aligning these with isotopic trends may prove difficult. Nevertheless, I have found some compelling chronological shifts which I will explore in this section.

![Figure 7-23: Bag plot of Early Medieval bone $\delta^{13}C_{col}$ and $\delta^{15}N_{col}$ values from England by broad date category.](image-url)
As with tooth enamel in Chapter 6, I combined date categories into broader periods due to sample size issues for some categories, and to mitigate the influence of regional sampling biases for certain sub-periods. As above, sex categories have been integrated here. Figure 7-23 highlights significant isotopic shifts between the Iron Age/Roman period, the start of the Early Middle Ages and the Viking Age through into the Anglo-Norman period. At first the expansion of the loop of c.790-1066+AD into the top righthand corner of the plot beyond the other periods seems to support this idea of a FEH. However, the bag (representing 50% of the data) has a high degree of overlap with the bags of both earlier periods and sits entirely within the loop of c.350-790AD, and mostly within the loop of 200BC-450AD. This means that the individuals with these isotopically enriched diets represent a minority, ~25% of the values for this period (although not statistical outliers). These people plot amongst freshwater fish, domestic fowl, carnivores and omnivores from Figure 5-2, which is interesting for tissue enrichment factors, and trophic levels.

The earlier shift from the Iron Age/Roman period to the beginning of the Early Middle Ages, whilst not the main focus of my research, is still 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 does support theories for a high degree of dietary continuity (in terms of isotopic signatures) between the two periods (Banham and Faith, 2014c; Sakai, 2017).
I also interrogated the chronological data by tissue and element, beginning with enamel δ¹³C_carb values. All comparisons between periods are also supported by BEST tests in Appendix D. I did not include any enamel δ¹³C_carb data from Roman Britain for comparison in the database as it was not a main focus of my research (and also not commonly analysed as discussed above), so it is hard to say exactly what aspect of diet might be the cause of the ¹³C enrichment seen above in Figure 7-23. However, when I compared c.350-790AD and c.790-1066+AD, the changes are clearer than the overlap between periods seen in section 7.2.2.2. The ranges (4.3 and 3.9‰ respectively) and means (-14.2 and -13.8‰) are similar, but the differences in modality are more interesting. A BEST test comparing the two periods suggests no real difference between them in terms of mean or standard deviation (Appendix D). The two peaks for post-Roman/pre-Viking England are lower and ~1‰ apart, supporting my earlier observation of C3 terrestrial and freshwater based diets in England at this time with likely a large degree of mixing of these resources. For the later period c.790AD onwards, the sample size is considerably smaller, however the stronger separation of the two peaks suggests groups with more distinctively separated terrestrial C3 diets (the upper peak ~-13‰) and more aquatic diets (peak ~-14.5‰). The individuals in this later period are mostly from riverine/wetland settings across a variety of regions, so access to freshwater resources would not have been an issue, and regionality is less of a concern with resource consumption. The
main sites in this period are all multi-modal, representing a split in foodways within communities. Many of these communities (e.g. Ketton Quarry, St John’s Oxford, and Masham) have evidence for mixed origins from Chapter 6 and historical evidence for Scandinavian settlement but there are no clear-cut distinctions with foodways and migration signatures. This could be an avenue for more in-depth analysis as it was not directly investigated here.

In dentine I found that the shape and range of $\delta^{13}C_{coll}$ distributions between the Roman and post-Roman/pre-Viking period are extremely similar, with a BEST test not able to detect any difference between them. However, this could change with more data from the Roman period since $n=10$ in my sample. An increase of less negative values post-790AD is noticeable, with the distribution shape of c.450-790AD effectively flipped. The BEST test results between these two periods found a difference which does not span zero (0.64 MDM) but is less than $1.3 \pm 0.6\%$o (average consumer-prey offset, see above), so may not signify any biologically or culturally substantial change in isotope values as with differences between the sexes above.

Figure 7-25: Violin plot of Early Medieval dentine $\delta^{13}C_{coll}$ values from England by broad date category.
Dentine $\delta^{15}N_{coll}$ values, as above, have a small sample size for the Iron Age/Roman period, making interpretation difficult, but the MDMs and SDs between 200BC-450AD and c.450-790AD were found to be essentially the same by a BEST test. Changes from c.450-790AD to post-790AD occur in almost every descriptive statistic and aspect of distribution shape. The ranges (8.8 and 10.5‰) and means both actual (10.8 and 12.7‰) and from the PPDs (10.7 and 12.7‰) differ by ~2‰ with the BEST test MDM not spanning zero. The distribution shapes in Figure 7-26 are substantially different and have strong similarities with those seen for their respective enamel $\delta^{13}C_{	ext{uct}}$ values, which is encouraging as these tissues formed at similar times of life, with enamel carbonate reflecting whole diet and dentine $\delta^{15}N$ protein intake. This further supports my hypothesis of two distinctive protein sources and varied trophic levels. This all supports a significant difference in consumption and diet from the end of the eighth century AD and it aligns with major shifts seen in enamel $\delta^{18}O$ values in the previous chapter, which will be discussed more below and in Chapter 9.
Diachronic shifts in bone are different to dental tissues; there is a large drop in bone \( \delta^{13}C \) values at the end of the Roman period. This shift is supported by a BEST test but has a difference in PPD means of 0.73‰ which is not large. However, the strong peak and overall shift in distribution to more negative values add weight to my argument of an increase in freshwater resource consumption during the Early Middle Ages. Despite the MDM not spanning zero for differences between c.350-790AD and c.790AD onwards, the difference is equivalent to machine error so little can be said in terms of the means. However, the differences in distribution shape and range show more variety in bone \( \delta^{13}C \) values for the later period which matches with trends from enamel and dentine. Overall the larger ranges and drop in means seen from the end of the Roman period, with distributions more skewed towards lower \( \delta^{13}C \) values from the fourth/fifth century onwards, support all the other analyses above. Most people had a C3 diet of both terrestrial and freshwater resources with no substantial or widespread marine consumption in adulthood.
The bone $\delta^{15}N_{\text{coll}}$ data in Figure 7-28 closely mirrors the dentine $\delta^{15}N_{\text{coll}}$ data in Figure 7-26 with increasing means and maximum values, with more positively shifted distributions over time. The BEST tests between periods for bone $\delta^{15}N_{\text{coll}}$ indicate that these differences are real, although the shifts are small with ~1‰ jump in mean per period. Despite the complexity in the carbon data, the fact that I have found these trends in both dentine and bone leads me to think these chronological shifts are real and driven by a variety of non-marine resources.
Figure 7-29: Bagplots comparing c.350-790 AD and c.790-1066+ AD through the life course using the same matched tissue data and approach from Figure 7-20 above, coloured by period. a) $\Delta^{13}C_{\text{dentine-bone}}$ and $\Delta^{15}N_{\text{dentine-bone}}$ b) $\delta^{15}N_{\text{dentine collagen}}$ and $\Delta^{13}C_{\text{enamel-dentine}}$ c) $\Delta^{13}C_{\text{enamel-dentine}}$ and $\Delta^{13}C_{\text{dentine-bone}}$ d) $\delta^{13}C_{\text{bone collagen}}$ and $\Delta^{13}C_{\text{enamel-dentine}}$. 

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The 3D scatterplots in section 7.2.4 showed no obvious differences in dietary change over life course by chronological phase (Figure 7-19). The same general trend is present in both periods with δ¹³C values correlating in all three tissues (see Figure 7-18), and in both periods there was little to no evidence for marine consumption using Δ¹³C enamel-dentine alongside δ¹³C values from dentine collagen and enamel carbonate (Figure 7-22). Chronologically increasing δ¹⁵N values in dentine and bone with these other trends leads me to think that the chronological trends I am seeing were not the result of a straightforward increase in marine fish, or even just of more protein in the diet generally as some of the zooarchaeological evidence may suggest (Crabtree, 1989; Orton et al., 2017; Rizzetto et al., 2017). To interrogate this further I re-visualised Figure 7-20 and Figure 7-21 by period.

Figure 7-29 a) shows that there is no real directionality or change over lifetime for individuals in c.350-790AD in terms of dietary protein. There is an elongation of the bag plot for people post-790AD, with a clear shift towards more negative Δ¹³C dentine-bone and Δ¹⁵N dentine-bone values. This is consistent with increasing protein over the life course. I have already shown this cannot be from marine protein to any large degree, so this protein must be terrestrial and/or freshwater as I have already demonstrated. Figure 7-29 a) also shows some continuity with half the bag and loop overlapping, so post-790AD still has many individuals with negligible change in diet over their life course.

Figure 7-29 b) demonstrates that individuals with higher δ¹⁵N dentine coll values post-790AD are likely outliers since the bag and loop do not extend to the highest values seen in Figure 7-26. It also shows that the period c. 350-790AD has a far larger range and diversity in δ¹⁵N dentine coll values but also in trophic positions indicated by Δ¹³C enamel-dentine values, than later individuals. From 790AD onwards the population has a tighter δ¹⁵N dentine coll range, occupying trophic levels akin to terrestrial herbivores and omnivores in childhood.

Figure 7-29 c) reinforces the lack of a shift to marine/C₄ resources in an individual’s lifetime in either period with no Δ¹³C dentine-bone values beyond ±1‰. Again, the later period’s bag and loop are far more restricted, indicating homogeneity in the group. The bagplot centres around Δ¹³C enamel-dentine values of ~6.5‰, again suggesting people
in this later period did not consume high levels of protein (from any source). The earlier period spans a wider range of $\Delta^{13}C_{\text{enamel-dentine}}$ values, showing the diversity in foodways for this part of the Early Medieval period.

Figure 7-29 d) further reinforces trends discussed above. There is a high degree of overlap between periods with both firmly within $C_3$ ranges for their loops and central bags. The later period sits toward the top of the $\Delta^{13}C_{\text{enamel-dentine}}$ range, not going below 5‰, thus ruling out any significant protein consumption, especially from marine sources during this period.

![Diagram](image)

*Figure 7-30: Bag plots of $\Delta^{13}C_{\text{enamel-dentine}}$ and $\delta^{13}C_{\text{carb}}$ for Early Medieval England by period.*

Figure 7-30 highlights that for the small proportion of individuals in the period c. 790-1066+ AD with higher trophic levels ($\Delta^{13}C_{\text{enamel-dentine}}$ values of ~4‰) who are more evident in the violin plots (Figure 7-24, Figure 7-25, Figure 7-26 and Figure 7-27) their $\delta^{13}C_{\text{carb}}$ values indicate this trophic position is due to freshwater resources. This is the same for the earlier period as well with a strong trend for both broad time periods matching the overall pattern from Figure 7-21 above. I have seen 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 7-24, Figure 7-25, Figure 7-26, Figure 7-27, and Figure 7-28 where chronological change from c.790 AD is more apparent.
Overall, 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 show that, aside from a few outlying individuals with some tenuous marine dietary signatures, there is no evidence for the FEH up to the eleventh century using multi-tissue analyses. For bone 119/2023 \( \delta^{13}C \) and \( \delta^{15}N \) signatures in England are classified by UML as bone cluster 2.1 or 2.2 (marine/C\(_4\) diets). 49 of these are Roman, a further 23 are juveniles from Raunds Furnells (probably osteological paradox and breastfeeding signals rather than marine consumption), and many of the rest 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 \( \delta^{13}C \) and \( \delta^{15}N \) 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 digital appendices), 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 \textit{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 (especially using the dentine \( \delta^{13}C \) and \( \delta^{15}N \) values or graphs like Figure 7-23). However, the lack of a marked increase in bone \( \delta^{13}C \) through time, and the use of tissue enrichment factors alongside enamel carbonate indicates that this shift in \( \delta^{15}N_{\text{coll}} \) 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, zoological 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, 2003; Barrett et al., 2004a; Barrett and Richards, 2004; Dobney, 2007; Orton et al., 2017; Reynolds, 2015; Serjeantson and Woolgar, 2006).
How can we reconcile this evidence? There is an increase in $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$ values through lifetime for some individuals post-790AD. There is evidence for freshwater consumption in both periods, but more so for c.350-790AD, and a significant number of individuals in both parts of the Early Medieval period with low trophic enrichment factors. For these individuals who have $\delta^{15}N_{\text{coll}}$ values (from either tissue) that we would usually associate with animal protein consumption ($\sim 8\%$ or higher) but whose $\Delta^{13}C_{\text{bioapatite-collagen}}$ values indicate “herbivorous” diets what could be causing this if not animal protein? Recent research suggests this could be due to crop stable isotope values, with increases in $\delta^{15}N$ seen through time seen for oats and barley (which typically have low $\delta^{13}C$ values approx. -23 to -26$\%$) at Stafford due to changes in agricultural practice and extensification (Hamerow et al., 2020). Changes to the types of cereals grown, their quantities and how they were grown are interesting to consider in light of the increased “brewing and stewing” signal for ~790AD seen in Chapter 6. This, combined with the evidence in this section, may point to a more plant-based explanation for changes in diet across the Early Medieval Period. This small case study by Hamerow et al. (2020) has limited samples but offers some other interesting avenues for discussion in Chapter 9. It seems the increased demand for fish seen in the zooarchaeological evidence probably made up <20$\%$ of whole diets, and so was isotopically and metabolically swamped by these terrestrial signatures and so is invisible in all tissues here.

The lack of precise dating for unfurnished and churchyard burials means that I have been unable to provide in-depth chronological resolution for dietary change in Early Medieval England with many date category overlaps in the dataset (due to a lack of grave goods and radiocarbon dates). The small sample sizes for post-1000 AD burials, especially for enamel $\delta^{13}C$, made pre- and post-1000 AD comparisons impossible and limited the multi-tissue work considerably. There is however isotopic evidence for an earlier freshwater FEH. People in Early Medieval England had predominantly C$_3$ based diets which included a variety of resources, and this varied with local environment and even within communities.
Recap of main findings:

- Diet does change in Early Medieval England at multiple points and in different ways.
  - Change after the Roman period towards a heavier reliance on freshwater resources alongside C₃ terrestrial plants and animals.
  - ¹⁵N enrichment through time, peaking after the late eighth century.
  - Increased protein over the life course in the period after c. 790 AD.

- Using multiple tissues and Δ values is key to looking at protein sourcing and trophic levels, especially when dealing with humans and the wide variety of ecosystems they exploit.

- More variety in trophic levels and diets c.350-790 AD than post-790 AD.

- If there was a FEH, as previous work and the zooarchaeological evidence suggests, this did not form a major part of the diets of Early Medieval people in England.

- People from c.790 AD onwards have lower than expected trophic positions given ¹⁵N enrichment evidence in their dentine and bone collagen.

- There was definitely a change in diet resulting in ¹⁵N enrichment through time, but this may be the result of the agricultural revolution, freshwater resources and/or more terrestrial protein sources in the diet.

7.3 Chapter Summary

This chapter began with comparing diets across Early Medieval western Europe and showed clear north-south gradients in dietary patterns in both bone and dentine. So how does diet in England compare to the rest of western Europe in the Early Middle Ages? England is most like its Frankish neighbours and the Skagerrak-Kattegat-Jutland basin in terms of diet in both childhood (dentine) and adulthood (bone). England has only a handful of individuals whose dietary clusters match with C₄/marine patterns and these people are likely migrants bringing their homeland isotopic signatures with them.

The (marine) Fish Event Horizon (FEH) is evident in human tissues but this phenomenon is sometimes hard to disentangle from millet consumption in certain regions (the Mediterranean) when multi-tissue data and offsets are not available. The
FEH is clear in the Baltic, Atlantic and Arctic Norway and Scotland and the Scottish Isles but is not prevalent in other regions of Early Medieval “Viking” settlements, England included.

There are very few differences in childhood versus adult diet in Early Medieval England, with some suggestion of $^{13}$C and $^{15}$N enrichment over the life course for some individuals post-790 AD. However, overall diets remained virtually the same regardless of life stage. The impact of survivorship is considerable and there is isotopic evidence for “stress” in many juveniles.

There is no isotopic evidence for any sex or gender-based dietary differences in Early Medieval burials. Further to this there is no evidence equating social status or different burial practices and diet.

Ultimately diet does change in England over the course of the first millennium AD. In the post-Roman period c.350-790 AD diets are firmly $C_3$ based, with a variety of terrestrial and freshwater resources being exploited to different degrees in different areas. Sometime around the end of the eighth century, or perhaps later, diet changes again but not as expected with the FEH. Low $\Delta^{13}$C$_{\text{bioapatite-collagen}}$ values indicate that $^{15}$N enrichment in this period might be due to other agricultural practices and foodways rather than increased animal protein. The similarity in the chronology of the changes described in this chapter with those seen in Chapter 6 for $\delta^{18}$O values suggests that large scale socio-economic changes around the end of the eighth century meant significant changes to everyday life and consumption in Early Medieval England.
8 Case Studies: Kent and East Sussex, and Finglesham

Since the previous three chapters were meta-analytical in nature, here, I use that large-scale analysis to inform analyses and interpretations of smaller scale regional and site-specific communities in Early Medieval England. It is difficult at the broader scale to discuss individual graves or more localised trends in any great detail. Therefore, the aim of this chapter is to interrogate the stable isotope and archaeological data together on two smaller scales – kingdom and community. The kingdom in question is the Kingdom of Kent (and a few cemeteries from just outside its modern borders in East Sussex and east Surrey) and the community is the cemetery at Finglesham in Kent. I demonstrate here the power of a multi-proxy, multi-isotope and multi-tissue approach for regional and site-specific investigations. The environmental and cluster analyses are of particular interest here – how does the unique position of Kent both geographically and politically impact on its human isotopic patterning alongside its material culture and historical narratives? The isotopic variation and outliers within Kentish cemeteries will be considered in light of their burial provisioning, allowing me to investigate if patterns differ at more localised scales from the large-scale analyses in the last three chapters.

8.1 Introduction and choice of case study region and cemetery

The choice of Kent and the most easterly portion of East Sussex, as the case study region lies in its unique geographical position and archaeology. Kent and East Sussex are the closest part of Britain to continental Europe, forming a wide peninsula in the southeast. This proximity has meant a continuous flow of people, ideas and material culture across the channel for millennia. This, coupled with its relative isolation from the rest of southern England through minimal land borders, resulted in a distinctive regional cultural identity which is reflected in its material culture (Richardson, 2005: 2; Brookes and Harrington, 2010; Harrington and Brookes, 2012).

Until the eighth century AD, Kent seems to have enjoyed relative independence in governance from the other Early Medieval English kingdoms, and for parts of the sixth and seventh centuries may have even been the dominant power in the south of the island. It later became a vassal state of Mercia in the eighth century and then of Wessex in the ninth before becoming subsumed into “England” in the tenth.
Æthelberht is the first historically well-attested “Anglo-Saxon” king in Bede’s *HE*. It is through Æthelberht’s marriage to the Frankish princess Bertha that (according to Bede) the conversion of the English to Christianity was facilitated (Stenton, 1971: 59–60; Blair, 2003: 27–28, 116–117; The Venerable Bede, 2009: 39–41; Brookes and Harrington, 2010: 44, 69–70). However, links with the continent were already long-established, and for some of the sixth century there is evidence to suggest Kent could have been under Merovingian control (Brookes and Harrington, 2010: 46–47). Frankish material culture is not uncommon in Kent and is almost entirely absent in other parts of southern Britain (although also present along the south coast and not uncommon on the Isle of Wight), emphasising this special cross-channel relationship (Brookes and Harrington, 2010: 46–47; Sorensen, 1999; Soulat, 2013, 2018).

Figure 8-1: Map of Kent and East Sussex showing cemeteries and other sites mentioned in this chapter.

The physical geography of the southeast is part of what makes the region so archaeologically interesting. It is defined by four major environment components – its rivers, the coastline, the chalk downlands and the Weald. There are good harbours and defensible (but eroding) coastal cliffs, but also good river links inland, including the Darent, the Medway, the Stour and the Rother. These rivers and their tributaries criss-cross Kent and East Sussex connecting the Weald and downland to the ports and
ultimately to the rest of Europe (Figure 8-1). The region is well placed for not only cross-channel trade but up into the North Sea, with several wics/emporia established by the eighth century, including Rochester, Sarre, Fordwich, Sandwich, Dover and Sandtun (Brookes and Harrington, 2010: 83; Hill and Cowie, 2001; Leggett, 2016; Pestell, 2011).

The complex geology of the region can be broadly simplified into bands centred around the Weald (Figure 8-2). Recent beach and river alluvial deposits of sand, silt, gravel and clay are found to the north, along the coast and estuaries and particularly in the marshlands. Then there is a band of chalk wrapping from Margate and Dover around to Eastbourne, followed by an inner ring of mudstone, sandstone and limestone, within which sits the Wealden geological groups – mudstone, siltstone and sandstone (British Geological Survey, 2019, n.d.; Brookes and Harrington, 2010: 10–14; Hill, 1981: 4–5). These younger and predominantly calcareous geologies should equate to relatively low $^{86/87}\text{Sr}$ values in human tooth enamel for the region (as discussed in Chapter 5).

Evidence for Early Medieval settlements in Kent and East Sussex is sparser than the funerary archaeology for the period. In the north on the more fertile soils there appears to be settlement continuity from the Roman period up to the seventh/eighth centuries. In the rest of the region, settlements were small and rural during the earlier part of the post-Roman period with a hiatus or supposed ‘Middle Saxon Shift’
from the eighth century until the tenth/eleventh century (Arnold and Wardle, 1981; Crabtree, 2018: 86–137; Hamerow, 1991; Leggett, 2017; Thomas, 2010; Wright, 2015). The tenth and eleventh centuries saw the old Roman towns regain their urban status but, unlike other parts of England, nucleated settlements do not seem to occur outside of the old Roman towns and ports (Fleming, 2013: 217–341; Leggett, 2016; Richardson, 2005: 55–77). This shift in location or hiatus of occupation is also apparent in the funerary evidence (Richardson, 2005: 55–77).

Recently, excavations of high-status settlements at Bishopstone (East Sussex) and Lyminge (Kent) by Gabor Thomas and colleagues have shone a spotlight on the complex nature of these seventh-ninth century “shuffles”, the fluid nature of these elite complexes and their hinterlands during the Early Medieval period (Knapp, 2018; Maslin, 2018; Thomas, 2010, 2013, 2018; Thomas et al., 2017; Thomas and Knox, 2012). These two sites are also the only sources of faunal stable isotope data for Kent and East Sussex, which I discuss below.

The funerary archaeology of Early Medieval Kent has a long history, with many antiquarian investigations and more recent development-led excavations. However, it is the excavations by Vera Evison and Sonia Chadwick Hawkes which established the chronologies and typologies for the region, and later, the sites excavated and published by the Canterbury Archaeological Trust which provided the evidence for our current understanding of death and burial in Early Medieval Kent. The synthetic research undertaken by Andrew Richardson, and Stuart Brookes and Sue Harrington also deserves mention for synthesising the large corpus of cemetery material for the region (Brookes and Harrington, 2010; Harrington and Brookes, 2012; Richardson, 2005).

The funerary archaeology of the region is complex and shifts considerably across the first millennium AD. In the fifth and sixth centuries there is what some have described as a ‘top heavy’ burial population with elaborately furnished burials displaying wealth, status and arguably clear cultural signifiers in certain artefact types (Richardson, 2005). Across the late fifth and sixth century there are clear distinctions between “Jutish” and Frankish styles of grave goods, with the individuals buried with these objects seen as migrants, and the region having a distinctive “multi-
cultural” burial elite (Brookes and Harrington, 2010; Richardson, 2005). By the end of the sixth century the material culture of many of these elaborate burials seems to be “demonstrably Kentish” (Brookes and Harrington, 2010: 68). These distinctive “Kentish” styles of artefacts (mostly brooches) appear in Merovingian cemeteries across the Channel, reinforcing the idea of close ties between the regions (Soulat, 2009, 2016, 2018).

These cemeteries in Kent and East Sussex are frequently cited as key evidence in the debate around the “Adventus Saxonum” due to these distinctive female dress-styles which are seen by some as definitive proof of incoming groups (Brookes and Harrington, 2010; Härke, 2011; Richardson, 2005; Sorensen, 1999). These marked shifts in material culture are also coupled with large differences in stature between women and men in the fifth/sixth centuries which seems to disappear by the seventh/eighth (Richardson, 2005: 100–102, 252). This is used by Richardson and Härke to argue for men and women coming from different ethnic groups during the “Migration Period”, but it could of course be due to a number of other factors. This is something I have directly investigated below.

In the seventh and eighth centuries a large shift occurs in funerary practices across western Europe, generally termed the “final phase” of furnished burial (Brownlee, 2020; Welch, 2011). During this period in Kent and East Sussex large grave markings and barrows appear in field cemeteries, whilst more individuals with few or no grave goods also appear in the same burial grounds. The dynamics of power and religious belief seem to have shifted considerably during these centuries, although furnished burial seems to have been particularly entrenched in Kent and took longer to peter out here than in other regions (Brownlee, 2019: 185). Large barrow burials also appear outside of cemeteries along major routeways, and female graves have a significant peak in ostentatious displays before subsiding. During this period the sites of cemeteries shift from the mid to the top of the slopes in the chalk downland, and eventually disappear from the landscape (Brookes, 2007; Brookes and Harrington, 2010; Richardson, 2005). Elite centres like Bishopstone and Lyminge show that this marks a shift of elite burial to churchyards, and we know that the royal family of Kent had begun interring their dead in monasteries and churches with Æthelberht and Bertha, which removed the top of the region’s social strata from these field cemetery
funerary displays earlier than in other parts of England (Brookes and Harrington, 2010: 69–92; Richardson, 2005; Thomas, 2010; Thomas and Knox, 2012).

This early adoption of Christianity and shift to churchyard burial perhaps explains the lack of Kentish “princely” burials or bed burials found elsewhere in Early Medieval England (Brookes and Harrington, 2010: 77–78; Richardson, 2005: 255–256). There certainly seems to be a deliberate break in both cemetery sites and many settlements as part of this seventh-ninth century “shuffle” which may be ideological rather than purely due to Scandinavian disruptions. Ultimately Kent has a unique funerary archaeology, sharing aspects with its neighbours in southern England, as well as clear contact with Francia and Jutland, but also with a lot of its own uniquely “Kentish” material and practices.

The region’s fascinating natural and cultural landscapes make it an ideal study area for Early Medieval transitions. Kent and East Sussex’s particularly well recorded processes of religious conversion and contact across the first millennium AD make it somewhere we would expect to find individuals of mixed childhood origins, and the impact of migration, religious conversion, trade and exchange on foodways. I also selected it as the case study region due to the intriguing bimodality I described in the enamel carbonate values in Chapters 5 and 6, and what this could mean both ecologically and archaeologically for the region. Kent and East Sussex, until now, have been understudied isotopically with only a handful of site specific or single skeleton IA studies compared to regions like the Upper Thames Valley (Barclay and Stevens, 2015; Bayliss et al., 2013; Brettell, Evans, et al., 2012; Hannah et al., 2018; Hughes et al., 2018; Knapp, 2018; Millard, 2014; Thomas, 2010). The two sites with previous mobility IA data from more than one individual – Ringlemere and Eastbourne – have tantalising evidence for early long-distance migrants (Brettell, Evans, et al., 2012; Hughes et al., 2018).

There are 14 sites with isotopic data presented in this chapter whose locations in the region can be seen in Figure 8-1 above. These represent a good cross-section of environment types, dates, community sizes and funerary practices for the region. As mentioned above, due to changes in settlements from the eighth to the tenth/eleventh century there is a scarcity of cemeteries for these centuries, and no
one site represents the whole date range of Roman to Anglo-Norman. Therefore, the latest human isotopic data I have here is late eighth or early ninth century, from Bishopstone. This means this region is unlikely, with the present data, to show evidence for the trends I described in Chapters 6 and 7 which began in the late seventh/eighth centuries.

The sample sizes for enamel, bone, dentine and faunal bone are summarised by site in Table 8-1.

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>Ratio F:M:U</th>
<th>No. Enamel $\delta^{18}O$ entries</th>
<th>No. Enamel $\delta^{13}C$ entries</th>
<th>No. Enamel $\delta^{13}C$ &amp; $\delta^{15}N$ entries</th>
<th>No. Bone Coll $\delta^{13}C$ &amp; $\delta^{15}N$ entries</th>
<th>No. Dentine Coll $\delta^{13}C$ &amp; $\delta^{15}N$ entries</th>
<th>No. Faunal Bone Coll $\delta^{13}C$ &amp; $\delta^{15}N$ entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bishopstone</td>
<td>D-F</td>
<td>3:3:1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Buckland</td>
<td>A-D</td>
<td>12:6:0</td>
<td>12</td>
<td>12</td>
<td>0</td>
<td>23</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>Dover</td>
<td>B-D</td>
<td>1(U)</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cliffs End Farm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thanet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eastbourne</td>
<td>A-E</td>
<td>7:10:2</td>
<td>19</td>
<td>0</td>
<td>19</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Finglesham</td>
<td>B-E</td>
<td>17:29:0</td>
<td>40</td>
<td>40</td>
<td>0</td>
<td>44</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Galley Hill</td>
<td>C/D</td>
<td>1(M)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Holborough</td>
<td>B-D</td>
<td>8:11:3</td>
<td>16</td>
<td>16</td>
<td>0</td>
<td>19</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>Lyminge</td>
<td>D/E</td>
<td>1(U)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>134</td>
</tr>
<tr>
<td>Mill Hill, Deal</td>
<td>A-D</td>
<td>17:15:2</td>
<td>24</td>
<td>24</td>
<td>0</td>
<td>33</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>Neat's Court</td>
<td>E/F</td>
<td>1(M)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Sheppey</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polhill</td>
<td>B-D</td>
<td>20:24:2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>65</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ringlemere</td>
<td>B</td>
<td>4:1:2</td>
<td>7</td>
<td>0</td>
<td>7</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>St Peter's Tip</td>
<td>A-E</td>
<td>1:11:0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Zone 14 Anglo-Saxon</td>
<td>D/E</td>
<td>2:1:0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cemetery</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>120</td>
<td>93</td>
<td>28</td>
<td>210</td>
<td>95</td>
<td>144</td>
</tr>
</tbody>
</table>

Table 8-1: Kent and East Sussex isotopic data sample size summaries by site, chemical element and tissue.

The choice of Finglesham as the case study cemetery for Kent and East Sussex was clear – it has the largest sample size for all three tissues (bone, dentine and enamel) for the region. This allowed me to undertake more robust analyses and have well-informed interpretations which would not be possible for cemeteries with fewer individuals, or with only one tissue analysed. It is also a well-known, well-excavated and well-documented cemetery that has a good balance between female and male
graves and variation in levels of grave provisioning so as to not overly bias the dataset in other aspects.

Finglesham is close to the ports and their limbs at Sandwich, Deal, Ringwould, Walmer and Dover, as well as being close to two other cemeteries with isotope data – Mill Hill and Ringlemere. It is therefore well placed within the populated landscape of the region with easy links to coastal trade.

Finglesham was first excavated by Stebbing and Whiting in 1928-29, with further excavations by Sonia Chadwick Hawkes between 1959-67. Hawkes excavated 216 inhumation graves, 201 of which were osteologically analysed (Chadwick Hawkes and Grainger, 2006). I selected 46 for primary isotopic analyses. 45 individuals had rib fragments selected for isotopic analyses but one (grave 18) did not produce collagen of sufficient quality for analysis by mass spectrometry. I also analysed teeth (both dentine and enamel) of 40 individuals. 40/46 individuals analysed have more than one tissue with isotopic data, 38 have all three tissues with data included here. The cemetery was in use from the sixth to the eighth century AD and seems to represent a “normal” burial population in its age and sex profiles (Chadwick Hawkes and Grainger, 2006: 15, 324). The majority of burials are aligned W-E with heads to the west but there are some variations on this, as seen in Figure 8-3. The site also boasts many tumuli/barrows and graves with post holes and other wooden structures alongside plain earth-cut graves.

In the following section I take the region as a whole and use the environmental variation described in Chapter 5 and hierarchical clustering from Chapters 6 and 7 to investigate Kent and East Sussex’s Early Medieval foodways and migration histories. I compare across cemetery sites and through time within the region, as well as tackle questions of exogamy practices. I then do the same on a community level for Finglesham. As per Chapter 3 I employ the Detecting Deviating Cells (DDC) algorithm for both the region/kingdom scale and the community/cemetery scale (Raymaekers et al., 2020; Rousseeuw and Bossche, 2018). This allows me to detect “outliers” within the data subsets for a range of variables in a novel way and combine this with the other graphical and statistical analyses to get a better sense of which sites or individuals stand out or set the trends.
Figure 8-3: Site plan of the Early Medieval cemetery at Finglesham, Kent, with burials sampled for stable isotope analyses highlighted in green (after Chadwick, 1958: 29).
8.2 Kent and East Sussex – kingdom scale

Here I look at how the underlying isotopic variation and the trends I described in the last three chapters play out on a localised scale, and how this relates to the archaeology of the region. The analyses therefore take a slightly different approach to the meta-analyses in Chapters 5-7. I begin with the faunal $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$ isotope data for the region forming a rough baseline for human consumption before giving an overview of the nature of Early Medieval human isotopic patterns in the region. I use the outcomes of my hierarchical clustering analyses in Chapter 6 and 7 to look for isotopic conformity and divergence in Kent and East Sussex, and what this might tell us about foodways, mobility and identity in the region. I also look at more localised patterns of consumption through the life course, and differences between the sexes to see if exogamy is detectable at a kingdom level. Finally, I employ the DetectingDeviatingCells algorithm to further look for outliers and patterns in the cemetery communities of Kent and East Sussex, not just in their isotopic data but also in their stature, numbers of grave goods, grave orientation and distance to a contemporary ecclesiastical site. There are only two sites here not on chalk – Bishopstone and Neat's Court, Sheppey – totalling eight individuals, so the impact of geology will not be directly assessed here due to small sample sizes.
### 8.2.1 Faunal baselines

Figure 8-4: Scatterplot of faunal $\delta^{13}C$ and $\delta^{15}N$ data from Kent and East Sussex (Lyminge and Bishopstone) dating from the sixth-ninth centuries AD, n=144 (Thomas, 2010; Knapp, 2018).

Figure 8-4 shows the available faunal bone collagen $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$ data for Kent and East Sussex. The 144 points come from two sites dating from the sixth to the ninth century AD – Bishopstone and Lyminge (see Figure 8-1 above for their locations and Table 8-1 for sample sizes from each site). Trophic enrichment in both $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$ is apparent for omnivores, domestic fowl and carnivorous species (here mostly cats and dogs see digital appendices for more detail). All herbivorous species and most omnivores have clear C$_3$ dietary signals, with some suggestion of mixed C$_3$/marine diets for some domestic fowl, carnivores and one omnivore whose values are close to -17‰. These data are predominantly from Lyminge and the result of an in-depth doctoral study by Zoe Knapp on the zooarchaeological assemblages at the site, in conjunction with the “Cultural and Scientific Perceptions of Human-Chicken Interactions” project at the University of Oxford (Knapp, 2018; Thomas, 2010). Knapp’s work provides a robust understanding of changes in elite foodways and ecology from the sixth through to the ninth century AD in Kent. She found that in Phase II (c. eighth/ninth century) there are changes in the kinds and proportions of animals being eaten, which she interprets as early evidence for Christian fasting in England. This is manifested in greater amounts of fish, chicken and eggs being eaten at Lyminge. The isotopic values of the animals per se does not change over time, just

![Figure 8-4: Scatterplot of faunal $\delta^{13}C$ and $\delta^{15}N$ data from Kent and East Sussex (Lyminge and Bishopstone) dating from the sixth-ninth centuries AD, n=144 (Thomas, 2010; Knapp, 2018).](image-url)
their proportional representations, moving from a red-meat heavy feasting culture to one with more white meats in line with Christian practices and Lyminge’s shift from a palace/manor to a monastic site. Sadly, despite the presence of fish bone on the site there is yet to be any isotopic investigation of these animals in the region. When compared to the larger faunal datasets presented in Chapter 5, the Lyminge and Bishopstone animals sit well within the data from England and western Europe, with no stark differences in animal bone isotope values.

My main concern with these faunal isotope values are that they are from elite sites, and lack data from fish and more wild fauna, despite being present in the assemblages. Ideally there would also be data from more rural settlements in the region, but this has been hard to obtain. There may be differences between sites across the region that makes using data from two sites as baselines for a range of cemeteries problematic. However, the faunal data here do follow the general trends seen across Early Medieval England and Europe (Chapter 5 and 7), so they are taken here to be a tentative baseline.

8.2.2 Human data overview and cluster analyses
I will now address the human data for the region. The $\delta^{18}O_{MAP}$ values predicted (using the OIPC) for the region are between -7.9 and -6.9‰ (GJ Bowen, 2019). The BGS base-maps give the north of the region predicted $\delta^{18}O_{dw}$ values between -7.5 and -7‰ and human enamel $\delta^{18}O_{phosphate}$ values between 16.6-17.9‰, and the south $\delta^{18}O_{dw}$ values between -7 and -6.5‰, and enamel $\delta^{18}O_{phosphate}$ values between 17.7-18.7‰ (British Geological Survey, n.d.; Evans et al., 2012; J Evans et al., 2018). Due to the geological complexity of the region there is a wide range of $^{87}/^{86}$Sr values for Kent and East Sussex with alluvial/clay regions having bioavailable strontium values of 0.7086-0.7097, calcareous areas 0.7079-0.7086 and the sandstone/mudstone/limestone outcrops producing values of 0.7097-7113 (British Geological Survey, n.d.; Evans et al., 2012; J Evans et al., 2018).
Figure 8-5: Violin plots with box and jitter overlays for human isotopic data from Kent and East Sussex (left-right, top-bottom): $\delta^{13}$C\textsubscript{carb} (enamel), $\delta^{13}$C\textsubscript{coll} bone collagen, $\delta^{13}$C\textsubscript{dentine}, $\delta^{18}$O\textsubscript{phosphate} (SMOW) enamel, $\delta^{15}$N\textsubscript{coll} bone, $\delta^{15}$N\textsubscript{dentine}, $\Delta^{18}$O\textsubscript{dw-MAP} (Chenery), $^{87}/^{86}$Sr.
Figure 8-5 summarises the individual tissue and element data distributions for Kent and East Sussex which I described in Chapters 5, 6 and 7. Given the baseline information for the region and overall trends for England there are some interesting observations to be made. The enamel $\delta^{13}C_{\text{carb}}$ range (-15.4 to -11.9‰, mean -13.8‰) and distribution shape are very similar to England as a whole. The shape resembles the distribution shape for c. 350-790 AD in Figure 7-24 which fits with the dates for the sampled burials. This suggests, as for the rest of England, a predominantly C$_3$ diet with a range of terrestrial and freshwater resources in peoples’ diets. The bone and dentine $\delta^{13}C_{\text{coll}}$ values likewise resemble trends for England, with bone being more multi-modal with a wider range than dentine (-22.1 to -18.5‰, mean = -20.1‰, and -20.4 to -19‰, mean = -19.8‰, respectively). These complement the enamel data for a predominantly C$_3$ diet throughout the life course.

$\delta^{15}N_{\text{coll}}$ values are very similar across both tissues mirroring the findings from chapters 5 and 7 of a range of protein in the diets of individuals, with more positive values found in dentine than in bone. Two individuals are outliers with low bone $\delta^{15}N_{\text{coll}}$ values of 3.5 and 3.6‰, whereas the majority of people have values above 8‰. The lowest dentine $\delta^{15}N_{\text{coll}}$ value is 7.8‰.

The $\delta^{18}O$ enamel values and their bimodality are extremely interesting. The higher peak and the waist of the distribution roughly correspond with the split in values described in previous work (British Geological Survey, n.d.; Evans et al., 2012; J Evans et al., 2018). However, the lower peak is lower than ranges given by Evans and colleagues, and the maximum and minimum values do not correspond with modelled values for the region as discussed earlier. This is demonstrated more effectively with $\Delta^{18}O_{\text{dw-MAP}}$ values for the region. The lower peak becomes more pronounced with a considerable number of individuals (56/120) having values beyond ±2‰, and the upper peak and waist of the distribution falling within ±2‰ (64/120). I therefore interpret this subsample as having a roughly 50/50 split between local and non-local signatures with at least two drinking water sources on the basis of enamel $\delta^{18}O$ and $\Delta^{18}O_{\text{dw-MAP}}$ value bimodality before accounting for “brewing and stewing”. The non-local values are diverse, potentially coming from areas as far away as the Mediterranean and Scandinavia.
Sadly, only a small number of individuals from Kent and East Sussex have $^{87}/^{86}$Sr values available from their tooth enamel (n=28). All 28 $^{87}/^{86}$Sr values fall within the range given above for local geologies (0.7079-7113), but they do show movement of individuals within Kent and East Sussex, with people having spent their childhood on Wealden-type geologies buried on alluvial or calcareous soils and vice versa (Brettell, Evans, et al., 2012; Hughes et al., 2018). However, for some individuals their $\delta^{18}$O and $\Delta^{18}$O$_{dw-MAP}$ values do not fit with a childhood spent in Kent and East Sussex, and this will be explored more below through hierarchical clustering.

I have used the cluster designations from Chapters 5 and 6 for individuals at the kingdom level to look at variability and outliers. There was only one individual (Neat’s Court, Sheppey, cluster 2) with enamel carbonate and strontium values enabling them to be used in enamel Combination 1 (oxygen, strontium and carbon) clustering, so this combination will not be discussed for the region.

![Figure 8-6: Scatterplot of Kent and East Sussex human tooth enamel $\delta^{13}$C$_{carb}$ and $\delta^{18}$O$_{phosphate}$ values coloured by O-C cluster number from Chapter 6 with marginal density plots (n=93).](image)

The split between clusters 2 and 3 above in Figure 8-6 is 1:2 with 31 individuals in cluster 2 and 62 in cluster 3. This is more skewed than the overall split in England which is closer to 50:50 (see Chapter 6). The split in terms of individuals at different sites in each cluster varies, with cluster 3 tending to dominate in the cemeteries studied here (see Table 8-2). This clear bimodality and dominance of cluster 3 fits
with the overall trend seen in $\Delta^{18}O_{dw-MAP}$ values above in Figure 8-5. As discussed in Chapter 6, cluster 3, whilst present in high levels across most of northwest Europe, is most apparent in Atlantic and Arctic Norway, Scotland and the Scottish Isles, and the Irish Sea, giving this cluster a distinctive “Atlantic” flavour, suggesting that at least some of the individuals in Kent and East Sussex in this group may be from these regions. Those in cluster 2 are likely to be local or from other parts of continental Europe. The lack of any people assigned to cluster 1, which is characterised by C$_4$/marine consumers and most dominant in Mediterranean regions with incomers from central and eastern Europe, casts some doubt on earlier work which hypothesised a high number of migrants from eastern parts of Europe, and further supports a predominantly C$_3$ diet in this kingdom (Brettell, Evans, et al., 2012; Hughes et al., 2018).

<table>
<thead>
<tr>
<th>Site</th>
<th>No. Individuals in Combination 3 (O-C) Cluster 2</th>
<th>No. Individuals in Combination 3 (O-C) Cluster 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buckland Dover</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Neat’s Court, Sheppey</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Finglesham</td>
<td>11</td>
<td>29</td>
</tr>
<tr>
<td>Holborough</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Mill Hill, Deal</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>31</strong></td>
<td><strong>62</strong></td>
</tr>
</tbody>
</table>

*Table 8-2: Summary of numbers of individuals at each site in Kent and East Sussex assigned to enamel Combination 3 (oxygen and carbon) clusters 2 and 3.*

In Figure 8-7 the same split on the basis of $\delta^{18}O$ values can be seen as in Figure 8-6 with Combination 2 (oxygen and strontium) clusters 1.1 and 1.2. As above, all $^{87/86}Sr$ values are consistent with possible values for Kent and East Sussex geologies, and may represent some localised movement, or possibly from further afield. There is one outlier, Eastbourne grave 269, who is assigned to cluster 2.2.2. The region with the largest proportion of cluster 2.2.2 is the Po Valley, and I interpreted this cluster as representing migrants to the Po Valley from further east in Europe in Chapter 6. This individual is an outlier in her cemetery community not just isotopically but in terms of funerary treatment as well. The original investigators hypothesised that she may
have come from somewhere in central or eastern Europe, and my work supports that conclusion (Hughes et al., 2018).

![Figure 8-7: Scatterplot of Kent and East Sussex human tooth enamel δ¹⁸Ophosphate and ⁸⁷/⁸⁶Sr values coloured by O-Sr cluster number from Chapter 6 with marginal density plots (n=28).]

The other visible outlier above, in terms of ⁸⁷/⁸⁶Sr values, despite being in cluster 1.1, is another female buried at Eastbourne – grave 63. The original investigators suggested she might have grown up on the Weald, based on what they saw as “local” oxygen isotopic values but a strontium signature consistent with the Wealden group geology (see Figure 8-2) and not the calcareous geologies underlying Eastbourne (Hughes et al., 2018). However, Eastbourne grave 63 has a δ¹⁸Odw-MAP value of 2.1‰. This indicates that she may be from the Weald and might have consumed some brewed/stewed liquids causing slight isotopic enrichment, or she could be from further afield. Given the proportions of this cluster across western Europe shown in Chapter 6 I would suggest somewhere in the Irish Sea (Wales or Cornwall) or perhaps Normandy/Neustria. Even in this small sample of 28 individuals, the lack of people with high strontium values and cluster 2.1 or 2.2.1 designations rules out origins from older geological regions with depleted δ¹⁸O values such as parts of Fennoscandia. The origins of Kent and East Sussex’s “non-locals” in this study are diverse but with some regions of Europe now excluded.
In Figure 8-5 and in Figure 8-8 it is clear that Kent and East Sussex is fairly homogenous in terms of diet. There are three individuals who deviate from the dominant bone collagen cluster 1 – Polhill grave 83 (cluster 2.1, date category B/C), and Mill Hill grave 79 (date category A/B) and Zone 14 Anglo-Saxon Cemetery in Thanet grave 176055(176056, date category D/E) (both cluster 2.2). These three individuals are interesting as both clusters are present in very low proportions in England, as seen in Figure 7-4. Both clusters have distinctive regional weightings which indicate that these individuals in Kent and East Sussex could be migrants based on diet.

Bone cluster 2.1 is most prevalent in Atlantic and Arctic Norway, the Baltic and Norse settlements in Scotland and the Scottish Isles, and I associate it with $^{15}$N enriched diets, but not necessarily marine input in every case (although that does hold for the Norse and Baltic settlements) as many individuals in cluster 2.1 have bone isotopic signatures more consistent with terrestrial $^{15}$N enriched diets (see Figure 7-1 and Figure 7-2 which show $^{13}$C$_{\text{coll}}$ values of -21.1 to -14.4‰ and $^{15}$N$_{\text{coll}}$ values of 12.7-19.1‰). Cluster 2.2 is present in very low numbers in northwest Europe, but dominant in central Europe, and parts of the Mediterranean (Figure 7-4). It is characterised by individuals with either some $C_4$ consumption and/or marine input.
without the nitrogen enrichment seen in cluster 2.1. Therefore, the Polhill burial could be from somewhere in Fennoscandia based on dietary clustering and, given the early dates of the other two burials, they could be from somewhere near the Mediterranean or central/eastern Europe.

There are three other individuals who are visual outliers in Figure 8-8 but who are assigned to bone cluster 1. The infant from Lyminge is an outlier due to its comparatively enriched $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ values, this is likely due to the variety of factors discussed in Chapter 7 with infant and child values. There are also two female burials at Mill Hill with very low $\delta^{15}N_{coll}$ values and depleted $\delta^{13}C_{coll}$ values – grave 86 who has a high number of grave goods including two “foreign” objects and grave 100 with four grave goods which are not of any particular note. Sadly, there is no enamel data available from any of these dietary outliers to further investigate the links with their differential dietary patterns, foodways and mobility.

In terms of general dietary trends for the kingdom, when compared to the faunal baseline data, humans in Kent and East Sussex are generally occupying different dietary spaces from their companion animals (felines and canids), suggesting humans are eating less protein than these animals. Instead their values are closer to domestic fowl, omnivores and in some cases herbivores. This implies that whilst these animals might have been part of Early Medieval diets in Kent and East Sussex, they may not have been a regular part of meals, which is supported by the enamel carbonate data (more below). Furthermore, since the faunal isotope data are from predominantly later high-status settlements, they may not accurately reflect earlier foodways for elite and non-elites alike. Moreover, despite many of these sites being “coastal” and the potential for coastal marshland grazing in the area, there is no evidence of the sea-spray effect in bone isotopic data of humans or fauna. This, combined with the bone cluster analysis, suggests that people in Kent and East Sussex did not heavily exploit coastal or marine resources for food, even though they buried (and probably lived) near the coast, were involved in maritime trade/exchange and there is zooarchaeological evidence at Bishopstone, Dengemarsh, Lyminge and Sandtun for fishing (and whaling) (Gardiner et al., 1999, 2001; Knapp, 2018; Thomas, 2010). This implies strong cultural foodways dominating over convenient local resources which
were perhaps exploited seasonally or in times of need, with marine food sources making up a small portion of their overall diet (<20% for the most individuals above).

The similarities in values and marginal density peaks between Figure 8-9 and Figure 8-8 show that diet through the life course in Kent and East Sussex is very similar, following the trends I described in Chapter 7 for England. Only two individuals were outliers assigned to dentine cluster 2.2 – Buckland Dover grave 297 and Mill Hill grave 17. Both are males from date category B (450-580 AD) but there are no other obvious links between them. Dentine cluster 2.2 is not uncommon in England but is more common in Norse regions suggesting these two individuals might have grown up in Fennoscandia, or somewhere with similar foodways. Both of these individuals are assigned to bone cluster 1, and enamel Combination 3 (oxygen and carbon) cluster 3. This combination of clusters lends weight to a possible Fennoscandian childhood origin for these two males, with diet over life becoming more similar to others in their burial region.

8.2.3 Sex, diet and mobility

Above I highlighted how the funerary archaeology of this area has been used in the debate over the “Adventus Saxonum”. It has been widely assumed that there may be differences in the proportions of men and women who migrated to England during
the “Migration Period” if indeed any did at all, and that throughout the Early Medieval period exogamy would have been practiced to strengthen political ties and widen the gene pool in communities (Fell, 1986; Goody and Goody, 1983; Härke, 1997, 2003; Jewell, 2007; Pattison, 2008; Thomas et al., 2006, 2008; Wemple, 1981; Winney et al., 2012). Previous studies have shown that in the earliest post-Roman phases of cemeteries in Kent and East Sussex there is a large disparity in stature between the sexes which might indicate different origins for men and women (Richardson, 2005: 100–102, 252). Historical research also suggests that women were more likely to be adversely affected by food shortages and may have systematically had different diets, as mentioned in Chapter 7, which could impact their growth and stature (Hagen, 2006: 444). Given the bimodality in oxygen isotopic values and the intriguing dietary outliers above, I wanted to re-investigate the possible impact of sex on isotopic patterns at the kingdom level. No patterns based on sex or gender were found in Chapters 6 and 7 but these associations could be more localised and not readily apparent at a larger scale.

Figure 8-10 and Figure 8-11 show bone and dentine $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ values coloured by sex. In both figures there are no readily apparent differences or separation between females and males on the basis of diet from either tissue. Bone values are tightly clustered. There appears to be an offset in dentine $\delta^{13}C_{coll}$ values, with males slightly enriched in carbon. This increase is less than 1‰ so might be coincidental in the sampling and graphics, or due to minor physiological differences between the sexes, as discussed in Chapter 7.
Figure 8-10: Scatterplot of Kent and East Sussex human bone \(\delta^{13}C_{\text{coll}}\) and \(\delta^{15}N_{\text{coll}}\) values coloured by osteological sex.

Figure 8-11: Scatterplot of Kent and East Sussex human dentine \(\delta^{13}C_{\text{coll}}\) and \(\delta^{15}N_{\text{coll}}\) values coloured by osteological sex.
Another lingering question around sex and isotopic data concerns differential mobility during the Early Middle Ages. I found no definitive difference between females and males in their $\delta^{18}$O$_{\text{phosphate}}$ values or $\Delta^{18}$O$_{\text{dw-MAP}}$ values in Chapter 6. There are some slight differences over time but nothing substantial to prove differential mobility at any point across the period. Figure 8-12 shows that, for Kent and East Sussex, there is no difference between female and male mobility in the Early Middle Ages. Both (and un-sexed individuals too) show almost identical bimodality, means (female = -0.4‰, male = -0.7‰) and ranges (6.5 and 7.5‰). Males are slightly skewed towards more negative values but overall the distributions are very similar. A BEST test confirms these observations with the MDM, difference in standard deviations and effect size all spanning zero (Appendix D). This demonstrates why simply using the mean is not enough; it suggests that the majority of both sexes were “local”, whereas I know from Figure 8-12 and the other analyses above this is not the case. There is a substantial proportion of individuals outside ±2‰ from all sexes in similar numbers.
But what about differences between females and males through time? Due to the shorter chronological coverage, and small sample sizes for each date category across the cemeteries in this kingdom I am limited to looking at c. 450-790AD in Figure 8-13. This shows that, broadly speaking, this bimodality and long range is consistent in both osteological sexes through time. Not only that but that migration and/or “brewing and stewing” were consistent well into the seventh and eighth centuries AD far past the “Migration Period” and for some time before and after LALIA.

8.2.4 Chronological change
Since changes in mobility and consumption over time were so apparent at a larger scale, here I investigate diachronic changes at a smaller scale for Kent and East Sussex to see if they still bear out. Data from this kingdom only just reaches the eighth/ninth centuries, with the majority being fifth-seventh. Therefore, many of the significant changes seen in the late seventh century onwards in England in Chapters 6 and 7 are not expected to be visible in this subset.

Figure 8-14 combines the sexes and some of the smaller date categories above from Figure 8-13 to look at mobility through time. There are still some marked sample size problems particularly for A-D (c. fourth-seventh century AD) and D-F (c. 630-1000AD); however, multimodality is present throughout. The earliest period looks almost entirely “local” with two individuals over +2‰. This changes dramatically in period B-D with a very marked bimodality distribution with an over 1‰ gap between the two groups. I interpret this as a small group of “local” individuals, with some individuals either consuming brewed/stewed water, or coming from regions in Europe with enriched $^{18}\text{O}$, then a substantial group of incomers from depleted $^{18}\text{O}$ regions coming into Kent and East Sussex. This is in line with patterns seen in
Chapter 6 during date category C/D (the late sixth to late seventh century) with a “bottom heavy” more distribution and a more consistent range of $\Delta^{18}O_{\text{dw-MAP}}$ values from $+2.6\%_o$ to $-3.1\%_o$, and a substantially dropped median (0.4 to $-1.3\%_o$). The consistency of the bimodality across the smaller date categories in Figure 8-13 suggests this may be a true migration signature as it is persistent before, and during the LALIA event.

![Figure 8-14: Violin plot of Kent and East Sussex human tooth enamel $\Delta^{18}O_{\text{dw-MAP (Chenery)}}$ values through time.](image)

Figure 8-14 and Figure 8-15 show the constancy of dietary isotope patterns at the kingdom level through time. For $\delta^{13}C_{\text{coll}}$, aside from some outliers for each date category the range is always between -21 and -19%o highlighting once again the C$_3$ diets of this region. There are some changes in distribution shape and a slight drop in mean and median from A-C to B-D to C/D with a shift upwards in category D-F. However, the smaller sample sizes for the first and last date categories, and the small size of the shift (<2%o) makes it difficult to say anything conclusive about these changes.

$\delta^{15}N_{\text{coll}}$ values in Figure 8-16 show a very stable picture over time. The central tendencies, ranges and shape of distributions from the late Roman period through to the seventh century remain largely the same. There is a slight shift upwards in $\delta^{15}N_{\text{coll}}$ values in period D-F, although with such a small sample size it is hard to say anything definitive. Knapp’s (2018) research suggests that Christian dietary laws really came
into force, at Lyminge at least, during the mid-seventh century which saw increases in chickens and fish in refuse pits, which might explain the shifts in $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ values. With this in mind, as in Chapter 7, the slight downwards shift to more negative $\delta^{13}C_{coll}$ values in Kent and East Sussex with relatively stable $\delta^{15}N_{coll}$ values might suggest more freshwater resources in the diet.

![Figure 8-15: Violin plot of Kent and East Sussex human bone $\delta^{13}C_{coll}$ values through time.](image)

In Figure 8-17 the enamel $\delta^{13}C_{carb}$ values through time do not show a great deal of change between date category B-D and C/D (and D-F) in terms of summary statistics.

![Figure 8-16: Violin plot of Kent and East Sussex human bone $\delta^{15}N_{coll}$ values through time.](image)
I can see a slight pull towards more negative values, from the drop in the position of the more prominent peak and larger range. This slight shift may support the uptake of more freshwater resources in Kent and East Sussex from the seventh century, which is in line with Christian foodways. More enamel carbonate data from a wider variety of sites and date categories would help investigate this trend.

Figure 8-17: Violin plot of Kent and East Sussex human enamel $\delta^{13}$C values through time.

8.2.5 Change through the life course

In this section I briefly compare bone and dentine collagen $\delta^{13}$C and $\delta^{15}$N values from individuals with both tissues in Kent and East Sussex and use tissue offsets to look at dietary change, trophic level and whole diet in the population. Other tissue offsets are analysed as part of the DetectingDeviatingCells algorithm in the next section. In Chapter 7 I showed that there were no substantial differences between childhood and adult diets in England and I wanted to see if on the level of a smaller kingdom (and site) there were any significant deviations from this trend.

Figure 8-18 and supporting BEST tests (Appendix D) show that on the kingdom scale there is more of a difference between childhood and adult diet compared with England as a whole, but ultimately these differences are not very large. Dentine has a larger area for both the bag and loop but encompasses almost all of the bag and loop for bone. There seems to be a broader dietary range for individuals buried in Kent
and East Sussex earlier in life with this diet becoming more similar in the population later in life with a trend towards lower $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$ values in bone. This makes sense when we consider the varied regions and high levels of migration in the population, meaning that childhood diets reflect a broader geographical base of varying foodways, alongside some early life dietary enrichment as discussed in Chapter 7.

![Figure 8-18: Bag plot of bone versus dentine $\delta^{13}C$ and $\delta^{15}N$ in Early Medieval Kent and East Sussex on individuals with both tissues.](image)

Using the comparisons between tissues in Figure 8-19 it is clear that this dietary change over the life course is minimal for most individuals and there is no overall trend in this change for the whole kingdom (see plot c). $\Delta^{13}C_{\text{carb-dentine}}$ values show that there is a range of whole diet trophic levels in the kingdom, as there is for England generally, but these do not have any relationship with collagen $\delta^{15}N$ or $\delta^{13}C$ values. The diets are clearly $C_3$ based as seen in plots b) and d), and higher $\delta^{15}N_{\text{coll}}$ values do not necessarily equate to high animal protein and/or marine based diets as can be seen in plots a) and b).
Figure 8.19: Bag plots of Kent and East Sussex a) $\Delta^{13}C_{\text{carb}}$ vs $\delta^{15}N_{\text{dentine}}$ b) $\Delta^{13}C_{\text{carb}}$ vs $\delta^{13}C_{\text{dentine}}$ c) $\Delta^{13}C_{\text{dentine}}$ vs $\delta^{15}N_{\text{bone}}$ d) $\delta^{13}C_{\text{bone}}$ vs $\Delta^{13}C_{\text{carb}}$.
8.2.6 Detecting deviants and kingdom scale discussion

In this section, instead of looking at violin or scatter plots to investigate differences between sites and individuals, I am using the DetectingDeviatingCells (DDC) algorithm, outlined in Chapter 3, to look at the Kent and East Sussex human isotopic data together with some (numeric) osteological, funerary and other contextual data to find patterns and outliers (Raymaekers et al., 2020; Rousseeuw and Bossche, 2018). I compare the outcomes of this analysis with the patterns and outliers identified above to discuss diet, mobility, burial and identity within Kent and East Sussex during the second half of the first millennium AD.

Data from 237 individuals in Kent and East Sussex was put into DDC for analysis, which included all isotope data, including tissue offsets, bar \(^{87/86}\)Sr data which I excluded before analysis due to the low sample size and number of sites represented. Of these 97 individuals and 13 variables were deemed suitable for analysis by the algorithm (Appendix G). The variables are:

- Number of grave goods
- Grave Orientation (degrees)
- \(\delta^{13}C_{\text{bone coll}}\)
- \(\delta^{15}N_{\text{bone coll}}\)
- \(\delta^{13}C_{\text{dentine coll}}\)
- \(\delta^{15}N_{\text{dentine coll}}\)
- \(\delta^{13}C_{\text{carb (enamel)}}\)
- \(\delta^{18}O_{\text{phosphate (SMOW)}}\)
- \(\Delta^{13}C_{\text{dentine-bone coll}}\)
- \(\Delta^{15}N_{\text{dentine-bone coll}}\)
- \(\Delta^{13}C_{\text{carb-dentine}}\)
- \(\Delta^{18}O_{\text{dw-MAP}}\)
- Distance to Contemporary Church (km)

The result is Figure 8-20 (p.304). The sites with burials included in this cell map are Finglesham, Ringlemere, Neat’s Court, Buckland Dover, Holborough, and Mill Hill. Some individuals only have one or two cells with data that is seen as deviant, others are completely yellow, indicating they are “normal” within the dataset. DDC flagged
two individuals of particular interest with a black spot at the end of the row – Mill Hill graves 17 and 73A. There are a further three individuals – Finglesham graves 15, 116 and 165 – with three or more deviating cells. DDC also flagged the cemeteries of Holborough and Mill Hill as being further away from roughly contemporaneous churches than the other cemeteries in the dataset (which interestingly is not flagged in the other cell maps when more sites are included).

For the five individuals with a high number of deviating cells in Figure 8-20, most deviate on linked dietary isotopes, for instance Finglesham grave 165 has lower than expected $\delta^{13}C_{\text{bone\ coll}}$ and higher than expected $\delta^{13}C_{\text{dentine\ coll}}$ with a higher than expected $\Delta^{13}C_{\text{dentine-bone\ coll}}$ value for the rest of their data. All five burials deviate in different variable combinations with no obvious links between them archaeologically or isotopically.

The two Mill Hill graves which DDC picked out as being particularly “deviant” are very different in what makes them stand out. Grave 17 is date category B (c. 450-580AD) and at male life stage 5, DDC deemed this individual to have higher than expected tooth values for $\delta^{13}C_{\text{dentine\ coll}}, \delta^{15}N_{\text{dentine\ coll}}$ and $\delta^{13}C_{\text{carb\ (enamel)}}$ which leads to being flagged for a high $\Delta^{15}N_{\text{dentine-bone\ coll}}$ value and a low $\Delta^{13}C_{\text{carb-dentine}}$ value. This tells me that this individual’s childhood diet and whole diet trophic level during childhood is peculiar given the rest of the dataset, and indeed the hierarchical clustering above in Figure 8-9 agrees. Mill Hill 73A on the other hand is a female at life stage 4 from date category B/C (c. 450-630AD); she stands out because she has a particularly well furnished grave (15 items) which mark her out using DDC, but she also has lower than expected $\delta^{13}C_{\text{coll}}$ in both her bone and dentine causing a higher than expected $\Delta^{13}C_{\text{dentine-bone}}$ value given her other data. However, these isotopic signatures are not peculiar in the dataset themselves per se just in combination with a high level of grave goods.

Finglesham grave 165 has already been mentioned above. Their $\Delta^{13}C_{\text{dentine-bone}}$ is the highest for the region by some way at 1.1‰, and their grave orientation (N-S) is also rare within the burials sampled. Their diet shifted the most in terms of $^{13}C$ over lifetime, but they are not flagged for $^{15}N$, so perhaps they could have changed foodways considerably in terms of terrestrial to more freshwater resources.
Finglesham grave 15 is another male, also at life stage 5, date category B (c. 450-580AD). They are flagged by DDC as having lower than expected bone and dentine $\delta^{13}C_{coll}$ values and with a higher than expected $\Delta^{13}C_{dentine-bone}$ value. These values do not stand out in and of themselves but might be flagged due to the rest of their seemingly “as expected” data, although this is hard to interpret.

Grave 116 is a male at life stage 4, dated to c. 580-690AD and is flagged as having lower than expected $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ dentine values with a lower than expected $\Delta^{13}C_{enamel-dentine}$ value in combination with the rest of their data. Their $\Delta^{13}C_{enamel-dentine}$ value of 4.18‰ is the lowest in the whole kingdom, and given this, they are one of only a handful of individuals who I would class as eating a lot of meat/being at a high trophic position. This is why their other values are seen as lower than expected as they are not marine in nature ($\delta^{13}C_{coll}$ -19.5‰ and $\delta^{13}C_{carb}$ -15.34‰) or particularly high in terms of $\delta^{15}N_{coll}$ at 11.3‰. Instead I suggest it indicates a diet high in freshwater resources. What is also interesting is that this individual is buried on a bed of chalk rubble and flint and may have originally had a barrow over their grave. Perhaps given this context and the date, they could be adhering to early Christian dietary laws as per the zooarchaeological evidence and the laws of Wihtred (Knapp, 2018; Whitelock, 1994).

Further to these “deviant” individuals, two burials were flagged by DDC in Figure 8-20 for $\Delta^{18}O_{dw-MAP}$, they are the only two Ringlemere burials kept by DDC due with more than one tissue analysed, and both were labelled as red for this variable. Intriguingly they are not flagged for their $\delta^{18}O_{phosphate}$ values and no deviant cells were identified for that whole variable in this DDC iteration. This certainly supports the original investigators’ hypothesis that these individuals might not be from England (Brettell, Evans, et al., 2012).

To mitigate the fact that some sites have only one tissue studied and thus were removed from the initial DDC analysis, I sub-setted the data to create two separate datasets, one with contextual columns and dietary data columns ($\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ from bone, dentine and enamel), and another dataset with contextual data columns, $\delta^{18}O$ and $\Delta^{18}O_{dw-MAP}$ without the dietary data. For the first subset this resulted in 162 individuals and 12 variables being analysed. In the second instance this resulted in
222 individuals with 6 variables (full details in Appendix G). The results can be seen in Figure 8-21 and Figure 8-22 respectively.

In Figure 8-21 the lack of tooth dietary data for Polhill and Bishopstone, and some other individuals at other sites is clear. Interestingly Polhill seems to be the only site where burials are not flagged for bone δ¹⁵N_coll, perhaps since it contributes the largest sample to the dataset. By comparison this inland site stands in stark dietary contrast to the other coastal and riverine cemetery populations. The Polhill population also has several individuals with lower than expected stature, perhaps suggesting different genetics and/or nutrition in the group. Buckland Dover and Mill Hill have more individuals who stand out with higher numbers of grave goods compared with contemporary furnished sites. DDC has highlighted four individuals as outliers in the dietary subset, summarised in Table 8-3.

<table>
<thead>
<tr>
<th>Cemetery and Grave ID</th>
<th>Date Category</th>
<th>Gendered Age Category</th>
<th>No. Grave Goods</th>
<th>No. Foreign Grave Goods</th>
<th>Grave Orientation</th>
<th>Body Position</th>
<th>Internment Style</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill Hill gr 17</td>
<td>B</td>
<td>M5</td>
<td>5</td>
<td>0</td>
<td>SSW-NNE (37°)</td>
<td>Ext. Supine</td>
<td>Earth cut grave</td>
</tr>
<tr>
<td>Mill Hill gr 73A</td>
<td>B/C</td>
<td>F4</td>
<td>15</td>
<td>1</td>
<td>SW-NE (41°)</td>
<td>Ext. Supine</td>
<td>Earth cut grave</td>
</tr>
<tr>
<td>Holborough gr 8</td>
<td>B/C</td>
<td>M4</td>
<td>4</td>
<td>0</td>
<td>W-E (90°)</td>
<td>Ext. Supine</td>
<td>Earth cut grave</td>
</tr>
<tr>
<td>Buckland gr 297</td>
<td>B</td>
<td>M4/5</td>
<td>11</td>
<td>0</td>
<td>NW-SE (133°)</td>
<td>Ext. Supine</td>
<td>Coffin, flint and chalk packing</td>
</tr>
<tr>
<td>Holborough gr 23</td>
<td>D</td>
<td>M4</td>
<td>1</td>
<td>0</td>
<td>W-E (90°)</td>
<td>Ext. Supine</td>
<td>Earth cut grave</td>
</tr>
<tr>
<td>Buckland gr 407</td>
<td>B</td>
<td>F4</td>
<td>10</td>
<td>4</td>
<td>NW-SE (142°)</td>
<td>Ext. Supine</td>
<td>Coffin?</td>
</tr>
<tr>
<td>Buckland 204</td>
<td>B</td>
<td>F4</td>
<td>15</td>
<td>3</td>
<td>N-S (163°)</td>
<td>Ext. Supine</td>
<td>Earth cut grave</td>
</tr>
<tr>
<td>Finglesham gr 15</td>
<td>B</td>
<td>M5</td>
<td>9</td>
<td>0</td>
<td>WNW-ESE (105°)</td>
<td>Ext. Supine</td>
<td>Earth cut grave</td>
</tr>
<tr>
<td>Finglesham gr 165</td>
<td>C/D</td>
<td>M5</td>
<td>3</td>
<td>0</td>
<td>N-S (174°)</td>
<td>Ext. Supine</td>
<td>Earth cut grave</td>
</tr>
</tbody>
</table>

*Table 8-3: Individuals with three or more deviating cells identified in dietary DDC Figure 8-21.*
Figure 8-20: DeviatingCells cell map for Kent and East Sussex drawn from $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N_{\text{coll}}$ bone and dentine, $\delta^{13}C_{\text{carb}}$ and $\delta^{18}O$ data, tissue offsets and numeric contextual data, $n=97$. Red cells = higher than predicted values, orange = slightly higher than predicted, blue=lower than predicted, purple = slightly lower than predicted, yellow = as predicted, white = missing value.

Figure 8-21: DeviatingCells cell map for Kent and East Sussex dietary isotopes and contextual data, $n=162$. Red cells = higher than predicted values, orange = slightly higher than predicted, blue=lower than predicted, purple = slightly lower than predicted, yellow = as predicted, white = missing value.

Figure 8-22: DeviatingCells cell map for Kent and East Sussex oxygen stable isotope data and offsets, and contextual data, $n=222$ burials. Red cells = higher than predicted values, orange = slightly higher than predicted, blue=lower than predicted, purple = slightly lower than predicted, yellow = as predicted, white = missing value.

NB: For full-size images of these cell maps see Digital Appendices.
Holborough grave 8 is flagged with a black dot as an outlying row which is intriguing since orientation is the only cell flagged as slightly higher than expected. At first glance at their contextual data and isotopic signatures they are a typical “final phase” burial buried W-E with a small number (4) of grave goods in an earth cut grave, and an extended supine position. It seems DDC has flagged them because other individuals with the similar isotopic signatures across all tissues tend to be buried on a slightly different axis (SW-NE), but otherwise there does not seem to be anything peculiar about this individual. Buckland Dover grave 297 was also flagged in Figure 8-9 as being assigned to dentine cluster 2.2 along with Mill Hill grave 17, and in Figure 8-20 for two instead of three cells (both $\delta^{15}N_{\text{coll}}$ values). In Figure 8-21 not only are they flagged for $\delta^{15}N_{\text{coll}}$ in both tissues but also their number of grave goods, which suggests when more cemeteries are included in the algorithm, the furnished burials at Buckland, Mill Hill and Finglesham stand out more in the region. Buckland grave 297 has the highest bone and dentine $\delta^{15}N_{\text{coll}}$ values of a non-juvenile in the DDC dataset in Figure 8-21. This burial clearly had a different diet in childhood and was at an extreme for $\delta^{15}N_{\text{coll}}$ values in adulthood as well. Given their $\Delta^{18}O_{\text{dw-MAP}}$ value of -4.5‰ and their elaborate funerary treatment I would suggest this male was of high social status and possibly a recent (c.10 years before death) migrant from somewhere to the north of the North Sea zone whose homeland foodways are still apparent in his rib collagen.

There are other individuals with three or more deviating cells whose contextual data can be seen above in Table 8-3. Finglesham 15 and 165 have already been discussed as they were also flagged in Figure 8-20, however Finglesham 116 is flagged by only two cells – lower than expected $\Delta^{13}C_{\text{enamel-dentine}}$ and lower than expected dentine $\delta^{15}N_{\text{coll}}$ – and not flagged in Figure 8-21 for dentine $\delta^{13}C_{\text{coll}}$, which might suggest that this is better contextualised and more “normal” given more individuals from other sites in the region. Holborough grave 23 was flagged as deviating in grave orientation (high), bone $\delta^{15}N_{\text{coll}}$ (high) and $\Delta^{15}N_{\text{dentine-bone}}$ (low). This individual has the largest negative $\Delta^{15}N_{\text{dentine-bone}}$ value in the kingdom, with their bone $\delta^{15}N_{\text{coll}}$ value 2.0‰ higher than their dentine, while the regional trend is generally the opposite with decreasing $\delta^{15}N_{\text{coll}}$ through life. Therefore Holborough 23’s life history may be of particular interest, especially as their $\Delta^{16}O_{\text{dw-MAP}}$ value (-1.3‰) is consistent with being local to the Holborough area. Perhaps this reflects a more local change of diet.
through the life course, as opposed to those individuals whose changes in diet through time may reflect mobility. The other two individuals are both from Buckland Dover, graves 204 and 407, and they both deviate in grave goods (high), orientation (high) and bone $\delta^{15}\text{N}_{\text{coll}}$ (low). These two women are indeed unusual in their funerary treatment, and although the number of foreign grave goods was excluded by the DDC algorithm, they are part of the minority in the region with 3-5 items of foreign origin. Their bone $\delta^{15}\text{N}_{\text{coll}}$ values are 8.8 and 8.7‰ respectively with little change over their lives (from dentine). Whilst not the lowest bone $\delta^{15}\text{N}_{\text{coll}}$ values in the region, the other high-status female graves with a large number of grave goods, and foreign goods have values 1‰ or higher than these two individuals, which is likely why the DDC algorithm flagged them.

I believe the homogeneity of the 65 individuals from Polhill in diet skews the other aspects of the dataset. Finglesham in particular has lower than expected bone $\delta^{15}\text{N}_{\text{coll}}$ values compared with them, which is interesting since they both have similar ranges. This could be a chronological shift like that described above here and in Chapter 7, as Polhill is predominantly seventh century burials, and thus later than most burials at Finglesham. Therefore, more individuals from each cemetery, and a better chronological balance, may change the outliers identified here.

In Figure 8-22 I have focussed on mobility and funerary data for DDC. Some broad trends which are immediately apparent are Polhill’s lower than average stature, Bishopstone’s position as a churchyard cemetery, and the earlier fifth-seventh century highly furnished burials at Eastbourne, Mill Hill, Buckland, and Finglesham. Perhaps most striking is that all of the analysed individuals at Eastbourne and Ringlemere are flagged as mobility deviants for both $\delta^{18}\text{O}_{\text{phosphate}}$ and $\Delta^{18}\text{O}_{\text{dw-MAP}}$, with no individuals from any other site flagged for these variables.

The individuals flagged by DDC with a black dot and/or with three or more deviating cells are identified with contextual data in Table 8-4. There is only one individual flagged as a row outlier – Buckland 414. They are a contextual outlier for grave goods (high), orientation (high) and distance from a church (high), but not flagged for any of their isotope values. The same can be said for Buckland 204 which has the same three deviating cells although was not flagged with a dot by the algorithm. This suggests to
me that, given their isotopic profile, the DDC algorithm would expect them to fit with later poorly or un-furnished graves which are closer to a church, which could have implications for the dating of this grave and its grave goods, and future research may target such outliers for radiocarbon dating.

<table>
<thead>
<tr>
<th>Cemetery and Grave ID</th>
<th>Date Category</th>
<th>Gendered Age Category</th>
<th>No. Grave Goods</th>
<th>No. Foreign Grave Goods</th>
<th>Grave Orientation</th>
<th>Body Position</th>
<th>Internment Style</th>
<th>δ¹⁸Ophosphate (‰)</th>
<th>Δ¹⁸Odw-MAP (‰)</th>
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<tbody>
<tr>
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<td>A/B</td>
<td>M5</td>
<td>9</td>
<td>1</td>
<td>SE-NW (322°)</td>
<td>Ext.</td>
<td>Stone Lined Grave</td>
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<td>N/A</td>
</tr>
<tr>
<td>Buckland gr 204</td>
<td>B</td>
<td>F4</td>
<td>15</td>
<td>3</td>
<td>N-S (163°)</td>
<td>Ext.</td>
<td>Earth cut grave</td>
<td>16.0</td>
<td>-2.0</td>
</tr>
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<td>Eastbourne 66</td>
<td>B</td>
<td>F4</td>
<td>12</td>
<td>1</td>
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<td>N/A</td>
<td>N/A</td>
<td>18.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Eastbourne 110</td>
<td>B-D</td>
<td>M5</td>
<td>2</td>
<td>0</td>
<td>S-N (0°)</td>
<td>N/A</td>
<td>N/A</td>
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</tr>
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<td>M4/5</td>
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<td>0</td>
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<td>N/A</td>
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<tr>
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<td>B</td>
<td>M4</td>
<td>3</td>
<td>0</td>
<td>S-N (0°)</td>
<td>N/A</td>
<td>N/A</td>
<td>17.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Eastbourne 649</td>
<td>B-D</td>
<td>F4/5</td>
<td>2</td>
<td>0</td>
<td>S-N (355°)</td>
<td>N/A</td>
<td>N/A</td>
<td>18.1</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 8-4: Individuals with three or more deviating cells identified in dietary DDC Figure 8-22.

The other individuals with three or more deviating cells are all from the Eastbourne cemetery:

- 66 – higher than expected values for grave goods, orientation and Δ¹⁸Odw-MAP and lower than expected δ¹⁸Ophosphate.
- 110, 680 and 795 all with flagged δ¹⁸Ophosphate and Δ¹⁸Odw-MAP values, and slightly lower than expected distance from a church.
- 649 – higher than expected grave orientation, along with flagged δ¹⁸Ophosphate and Δ¹⁸Odw-MAP values.

The whole cemetery is flagged for its oxygen isotopic values, so these individuals are not unique in this aspect, however aspects of their funerary treatment flags them in DDC. 110, 680 and 795 are intriguing, flagged as slightly lower than expected distance from a church when the whole cemetery has the same value for this variable, but it is clearly some other aspect of their funerary treatment which made this variable flag for them in particular. I suspect it is due to their low number of grave goods and S-N orientation being 0°, as the algorithm sees this as substantially different to S-N values closer to 360°, therefore I do not accept these individuals as outliers/deviants for
distance from a church. Similarly, 649’s deviating cell for grave orientation is due to the low number of grave goods and an orientation of 355° which actually fits with the other S-N burials but is an artefact of the algorithm. Grave 66 likewise suffers from the same problem with compass degrees and the algorithm, although its grave goods are unusually high in number for the cemetery, and very unusual for an individual buried S-N, so this combination of flagged cells as deviating may truly signify this unusual combination.

The fact that DDC only flags Eastbourne and Ringlemere (26 of 222 individuals) for $\delta^{18}O_{\text{phosphate}}$ and $\Delta^{18}O_{\text{dw-MAP}}$ values in Figure 8-22 lends weight to Brettell’s “Impious Easterners” hypothesis, as the majority of individuals have $\Delta^{18}O_{\text{dw-MAP}}$ values of $+2\%_0$ or above (Brettell, Evans, et al., 2012; Hughes et al., 2018). However, as discussed earlier, for individuals with values in this region, brewing and stewing effects must be considered, as Brettell does discuss (Brettell, Evans, et al., 2012; Brettell, Montgomery, et al., 2012). These cemeteries are not the only ones to give $\Delta^{18}O_{\text{dw-MAP}}$ values of $+2\%_0$ or above; similar values are also present for individuals at Finglesham, Neat’s Court, Buckland, Holborough, Mill Hill and Cliffs End Farm (the last was excluded from DDC due to over 50% NAs), so why are these two sites flagged by DDC? As these two sites were analysed as phosphate and not carbonate at Durham, rather than by myself at Cambridge or at BGS, there could be subtle differences in the data which make them stand out to the algorithm, despite all other carbonate data having been converted to phosphate (Brettell, Evans, et al., 2012; Hughes et al., 2018; Millard, 2014). By looking at the data and sites as put in, it is unclear what in particular is causing these individuals from these two sites to stand out in DDC. These sites are unusual as they are entirely skewed towards the same end of the scale for $\delta^{18}O_{\text{phosphate}}$ and $\Delta^{18}O_{\text{dw-MAP}}$ values, whereas the other cemeteries with $n > 1$ with isotope data also have this bimodality towards the other end of the range. Is this a computational difference, and chemistry methodology/lab-based difference, or a true reflection of these sites being substantially different in their oxygen isotopic signatures than the rest of the kingdom? Regardless, these two sites stand out in terms of $\delta^{18}O_{\text{phosphate}}$ and $\Delta^{18}O_{\text{dw-MAP}}$, their overwhelmingly “warmer” signature than is possible for Kent and East Sussex’s natural drinking water, alongside a minority of individuals from other sites with similar values. This suggests that this may indeed be
a true reflection of a different water source for some individuals in these communities, but methodological differences cannot be entirely excluded.

Interestingly since the algorithm looks at the dataset as a whole and not just by individual rows or columns, it may miss or smooth out some of the individuals identified as outliers by other methods. Therefore, because they are common in the dataset, individuals with negative $\Delta^{18}$O$_{dw-MAP}$ values are seen to be the “norm” for Kent and East Sussex, which means individuals who I would interpret as probably “local” can and do get flagged as “deviant” alongside those with higher $\Delta^{18}$O$_{dw-MAP}$ values. It is therefore imperative to look at the data itself and use other graphical and statistical methods alongside DDC, especially when a largely migrant population is hypothesised. This being said, the algorithm was very sensitive to the supposed migrants from Ringlemere and Eastbourne.

I therefore revisited the individuals with $\Delta^{18}$O$_{dw-MAP}$ values beyond $\pm2\%_0$ here and looked at their archaeological contexts more closely. There are 53 individuals with values outside of the $\pm2\%_0$ range, and they are found at Buckland, Finglesham, Holborough, Mill Hill, Eastbourne and Ringlemere in high proportions, as discussed above (see digital appendix for a list and contextual data). There is no straightforward pattern between these potential migrants and any particular aspects of burial practice and demography. Some of these individuals do have “foreign” grave goods but not all, and not all individuals with “foreign” grave goods had $\Delta^{18}$O$_{dw-MAP}$ values beyond $\pm2\%_0$. Moreover, the directionality and variety in magnitude of these $\Delta^{18}$O$_{dw-MAP}$ values suggested multiple origins/water sources for these 53 individuals. Even if I was to entirely discount individuals with values above $+2\%_0$, the range from -2 to -4.5$\%_0$ suggests migrants from other parts of Britain and much further north.

Not only am I proposing wide-ranging and varied migration into Early Medieval Kent and East Sussex from the fifth to the ninth century, and mixed communities of locals and migrants, but when we look at possible family groups within cemeteries there are some interesting observations. For example, the multiple burial grave 105 at Mill Hill (dated broadly to the fifth to seventh century B/C/D), Deal, of a child, adult female and adult male, is often assumed to be a “nuclear family”. Of course, without DNA it is impossible to tell if these individuals are related, but if we consider that they might be
their $\Delta^{18}$O$_{dw}$-MAP values are all the more interesting. The child (105A) and male (105B) have $\Delta^{18}$O$_{dw}$-MAP values of -2 and -3‰ respectively, while the female skeleton (105C) is the only one with a “local” value of 0.5‰. Their dietary isotopic signatures (dentine, bone and enamel $\delta^{13}$C$_{carb}$) however are all extremely similar. Burials 105A and B are enamel carbonate cluster 3, and 105C belongs to cluster 2. The male has 3 grave goods associated with him, the child none, whereas the woman has 22 items, including curated Roman coins and “Kentish” style brooches which lend weight to my interpretation of this woman likely being “local”. This could be an example of a blended family – non-local male and his child migrating to Kent, and marrying a relatively high-status local woman, and these dietary similarities reflect the close similarities in human isotopic niches across Early Medieval Europe. It is of course hard to prove, but regardless, their interment together in the same grave, more or less at the same time, is testament to the multi-origin, multi-cultural and integrated nature of Early Medieval Kent and East Sussex.

What of the hypothesis of differential migration of men and women to the region from the fifth century onwards? As discussed above, there is no clear evidence for any kingdom wide sex-based differences in $\Delta^{18}$O$_{dw}$-MAP values. If anything, the data here supports a burial population of very mixed origins across most sites. I agree with Richardson (2005: 252) that the archaeological record in Kentish (and East Sussex) cemeteries supports a model of high levels of migration throughout the Early Middle Ages. The isotopic evidence does not support a solely northern flavour to this migration as per “Adventus” narratives, although a very large proportion of $\Delta^{18}$O$_{dw}$-MAP and $\delta^{18}$O values do suggest a large influx of individuals from northern parts of continental Europe and Fennoscandia (Härke, 2011; Leslie et al., 2015; Pattison, 2008; Richardson, 2005; Sorensen, 1999; Thomas et al., 2006, 2008; Winney et al., 2012). The reality is inevitably more complex than previous work on migration to/in Early Medieval England has ever imagined. Some sites seem to be almost entirely made up of “non-locals”, others are a mixture of “locals” and “non-locals” sometimes with this mix within the same grave. This influx of people to Kent and East Sussex was not one event but instead my analyses support the model of multiple/continuous migration from the fifth to the ninth century AD, and likely continuing on from earlier mobility across the Channel and Europe more broadly. The origins of these migrants are diverse, and when the evidence from all three tissues and grave goods are
combined it shows that migrants to this area probably came from at least five different regions during from the fifth-eighth centuries AD:

- Irish Sea Zone
- The Mediterranean
- Central Europe (e.g. near the Moravian Massif)
- Northern continental Europe/Southern Scandinavia
- Other parts of Britain and Francia which are isotopically almost indistinguishable from Kent and East Sussex, based on grave assemblages.

Migrants from ‘warmer’ regions are hard to prove due to “brewing and stewing” however imported Mediterranean items do speak to long-distance trade links, so this is entirely plausible especially given previous studies in the region (Brettell, Evans, et al., 2012; Hughes et al., 2018). To build upon this picture, ideally more individuals would be analysed, particularly using strontium and enamel carbonate.

In terms of diet, the outcomes of hierarchical clustering and DDC highlight the homogeneity of Early Medieval diets across most of western Europe as described in Chapters 5 and 7. These methods have also identified outliers whose dietary signatures support their migration from particular regions.

There may be differences in diets between Polhill and the rest of the region, as evidenced by the DDC analysis (Figure 8-21) in terms of bone $\delta^{15}$N$_{coll}$ in particular, which may reflect differential resource availability and use at a truly inland site versus others which are close to the coast or a river. Change in diet over the life course reflects the diversity of childhood origins in the region, with diet becoming more similar over life, presumably while these individuals were in Kent and East Sussex. This really reflects the multi-origin nature of people in the region but also the dynamic nature of Early Medieval foodways and identities. Moreover, there is diachronic change in adult bone $\delta^{13}$C$_{coll}$ and $\delta^{15}$N$_{coll}$ values over time, with a downwards shift in both during the late sixth and seventh centuries, and then a slight shift upwards in the seventh and eighth centuries, and a change to more negative $\delta^{13}$C$_{carb}$ values in the seventh century (see Figure 8-15, Figure 8-16 and Figure 8-17) which aligns well with the zooarchaeological evidence presented by Knapp (2018).
Knapp showed that at Lyminge there were changes in agriculture and proportional representations of animals species from the seventh century onwards. She saw a decrease in the number of pigs especially in “feasting” contexts and an increase in chicken and fish bone through time. She equated these changes with an early adoption of Christian dietary laws as evidenced by the Laws of Wihtred of Kent (c. 695 AD)\(^{10}\) (Knapp, 2018; Whitelock, 1994). This meant a prohibition on terrestrial meat sources for large parts of the year, but fowl and fish were acceptable alternatives. The decrease in \(\delta^{13}C\) in both tissues during the seventh century holds with discussions of freshwater consumption in earlier chapters and might suggest freshwater fish were eaten more in replacement of meat than chickens as fowl \(\delta^{13}C_{\text{coll}}\) and \(\delta^{15}N_{\text{coll}}\) values tend to be more similar to omnivores and carnivores (see Figure 5-2 and Figure 8-4). The changes in \(\delta^{15}N_{\text{coll}}\) values in Figure 8-16 are so small that these could be biochemically insignificant, as values are still generally consistent with animal protein consumption, these shifts may reflect subtle differences in protein sources, but without fish isotopic data for the region it is hard to say more.

In the individuals here I do not have strong evidence for a large consumption of domestic fowl or marine fish, which may be due to the faunal baseline mismatch between the sites of Lyminge and Bishopstone, and the lack of fish bone isotopes for the region I mentioned above. However, the drop in bone \(\delta^{13}C_{\text{coll}}\) isotopic values alongside the changes I described in enamel carbonate (Figure 8-17) do suggest an increase in freshwater resource consumption for some of the population. This would be in line with some of Knapp’s observations and the documentary evidence. Sadly the small number of individuals from late seventh century contexts and later makes the increases seen in bone collagen isotopic values (Figure 8-15 and Figure 8-16) hard to extrapolate from. However, these data do support a move towards a diet more based on marine fish and/or domestic fowl as described by Knapp, but it could be isolated to high status Christianised manor-minster sites like Bishopstone which make up 7/13 of these later individuals.

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\(^{10}\) The laws of Wihtred state the following in regard to Christian dietary prohibitions: “If anyone gives meat to his household in time of fasting, he is to redeem both freeman and slave with healsfang. If a slave eat it of his own accord [he is to pay] six shillings or be flogged.” (Whitelock, 1994).
It is a surprise given all of the maritime activity evident in Kent and East Sussex that there is so little (if any) marine input to diet in these predominantly coastal communities. It seems that if people were exploiting these resources before the seventh and eighth centuries it may have been minimal and sporadic in nature. There is evidence for whale carcass processing at Lydd in Kent, although initial radiocarbon dates for the whales are later than most of our humans analysed here, c. 840-1043AD (Gardiner et al., 1999). It might suggest opportunistic exploitation of these resources, perhaps when animals became stranded, although whaling is attested in Ælfric’s colloquy in Dorset, it is unclear how common this activity really was in Early Medieval England (Aelfric, n.d.; Gardiner et al., 1999). Given the dietary patterns in Chapter 7 this seems unlikely to have been a common occurrence and large part of diets in England during the first millennium AD, although it is interesting to consider.

Overall Kent and East Sussex was a highly diverse kingdom with multi-origin inhabitants owing to its maritime links. The adoption of Christianity, and changes in economy may have changed diets in the region, but they seemingly did not alter the high level of mobility and diversity of individuals found in the cemeteries studied here.

Kingdom summary:

- High levels of mobility in Early Medieval Kent and East Sussex from the fifth to the ninth century.
- Migrants probably come from diverse origins – Mediterranean to Scandinavia.
- Mixed burial populations not segregated by childhood origin.
- No clear link between sex or funerary treatment and isotopic data.
- Slight dietary isotope change over time may align with early Christian dietary laws.
- Dietary change over the life course may reflect subtle changes in foodways from diverse childhood origins to localised foodways and resources in Kent and East Sussex.
8.3 Finglesham – community scale

Next I consider the cemetery of Finglesham in Kent to investigate the interplay between different isotopic patterns and funerary archaeology at a site-specific/community scale. As mentioned above, Finglesham is a large and well documented cemetery, close to the coast with burials dating from the fifth to eighth century AD. I personally undertook the isotopic analysis all of the individuals presented here as per the methods presented in Chapter 4. Of the 46 individuals analysed, 40 have tooth tissues with isotope data (both enamel and dentine) and 44 were analysed for bone all of which was rib (as per Table 8-1 and see appendices for raw data and database entries, Figure 8-3 for sampled burials within the cemetery). The spread of individuals across different date, age and sex categories is summarised in Table 8-5, with more individuals from periods C/D and D, and slightly more males than females in the sample.

41 individuals had stature estimates available and these range between 145-183cm, female graves range from 145-169cm, and males 165-183cm which agrees with the analysis undertaken by Richardson (2005: 100–102, 252). Therefore, I have investigated sex-based differences in mobility and diet for this community as I did for the whole kingdom above. Numbers of grave goods within the Finglesham subsample range from 0-13, with a maximum of two foreign items (as specified in the original reports) in one grave (gr 57). For reference, the $\delta^{18}O_{MAP}$ value I calculated for the site using the OIPC is -6.9‰ (see digital appendices) (GJ Bowen, 2019; Bowen and Revenaugh, 2003).
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<td></td>
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</tr>
<tr>
<td></td>
<td>M</td>
<td>29</td>
</tr>
</tbody>
</table>

Table 8-5: Summary of burials from Finglesham by date category, gendered age category (see Chapter 3) and osteological sex for which stable isotope analyses were undertaken.

I have utilised the hierarchical clustering outcomes from Chapter 6 and 7, as I did above for the kingdom scale, to assess the Finglesham population. Figure 8-23 shows the enamel $\delta^{13}C_{\text{Carb}}$ and $\delta^{18}O_{\text{Phosphate}}$ results for the cemetery, with similar multimodality shown at the site as is found for the region as a whole. This extends to the cluster designations for burials too, with enamel Combination 3 cluster numbers 2 and 3 present in the population. There are more individuals assigned to cluster 3 (29) than 2 (11), showing a mixed-origin group possibly dominated by individuals with enamel values more consistent with parts of northern Europe. Those individuals in cluster 2 tend to have $\Delta^{18}O_{\text{dw-MAP}}$ values consistent with being "local" but a few are close to or beyond +2‰ so they are not all definitively "locals" but could be if brewing and stewing are at play. Similarly, the individuals in cluster 3 tend to have $\Delta^{18}O_{\text{dw-MAP}}$ values close to or beyond -2‰.
Despite this diversity in enamel carbonate signatures, Figure 8-24 and Figure 8-25 demonstrate the homogeneity in diet signatures in both bone and dentine collagen in Finglesham. For both tissues all individuals were assigned to the same cluster (cluster 1 for both). However, this does not necessarily equate to homogeneity through the life course.

For bone, Finglesham has $\delta^{13}\text{C}_{\text{coll}}$ values ranging from -20.9 to -19.7‰ (1.2‰), and $\delta^{15}\text{N}_{\text{coll}}$ values between 8.4 and 10.9‰ (2.5‰). The ranges for dentine are similarly tight with $\delta^{13}\text{C}_{\text{coll}}$ values ranging from -20.4 to -19.3‰ (1.1‰), and $\delta^{15}\text{N}_{\text{coll}}$ values between 7.8 and 12.6‰ (4.8‰). There is little variation in $\delta^{13}\text{C}_{\text{coll}}$ values for either tissue, as expected given the kingdom data and discussions in Chapters 5 and 7. $\delta^{15}\text{N}_{\text{coll}}$ values in bone suggest at least two different trophic levels in the population. $\delta^{15}\text{N}_{\text{coll}}$ values in dentine show more variation which, as previously mentioned, could be due to variability in the types of teeth analysed although these do not appear to be systematically offset in any way (predominantly PM2 and M2 but some other teeth were analysed, see digital appendices). Instead I think this is due to the diversity of childhood origins in the population as discussed above for Kent and East Sussex as a whole. Overall the group has a C₃ based diet with little variation in the population, with no clear evidence for a substantial marine input into the diet.
There are no clear outliers in the Finglesham subsample identifiable using the hierarchical clustering groups from Chapters 6 and 7. This is a population with mixed origins whose dietary habits throughout life are relatively similar to one another. This is not unexpected for a smaller community buried together, where we might expect
more localised patterns of consumption on a small scale, especially in bone which is more likely to represent some or all of their time in and around Finglesham and its associated settlement(s).

In the following sections I look at chronological change in migration, dietary change over the life course and tissue offsets, and isotopic differences between the sexes before using the DDC algorithm to identify outliers in the Finglesham population.

8.3.1 Chronological change

Figure 8-26: Violin plots of Finglesham $\Delta^{18}O_{dw-MAP}$ (Chenery) values through time from c.450-790 AD.

Due to the low variation within the $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ values for bone and dentine in Finglesham, the relatively short time span the sampled burials represent and the skewed sampling towards those from date categories C and D, I have not looked at diachronic change for diet at the site. However, I have looked at change through time in $\Delta^{18}O_{dw-MAP}$ values at the site to see if any particular migration waves are identifiable. Figure 8-26 shows that even despite some small sample sizes for earlier dated graves, individuals with negative $\Delta^{18}O_{dw-MAP}$ values are present throughout the use of the cemetery. There are only a few individuals with positive $\Delta^{18}O_{dw-MAP}$ values, who belong to enamel carbonate cluster 2, one in date category B/C and the others from c. 580 AD onwards. I believe this shows that Finglesham is a community of migrant individuals to Kent in the earlier centuries from somewhere further north in
Europe (probably Scandinavia). The later more “local” and possible “brewing and stewing” signatures which appear one or two generations after the founding of the burial ground are therefore likely the locally born descendants of the original group. This picture could change with more individuals included from the earlier graves, and there may be this bimodality in the earlier phases too, in which case Finglesham would be a fully mixed local and migrant burial community from its inception. There are three individuals whose $\Delta^{18}O_{dw-MAP}$ values are 1.9, 1.9 and 2.6‰. Here I cannot rule out “brewing and stewing” effects or possible migration from somewhere further south in Europe, but without significantly different diets or strontium data it is impossible to say more.

8.3.2 Change through the life course

![Figure 8-27: Bag plots of bone versus dentine $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ in Finglesham.](image)

As with England and the kingdom scale above, I compared bone and dentine $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ values from individuals with both tissues analysed in Finglesham, the results of which can be seen in Figure 8-27. As with the bone and dentine scatterplots above, the ranges for $\delta^{13}C_{coll}$ are relatively small for both tissues ($< 2\%$), however the $\delta^{15}N_{coll}$ values in dentine are markedly higher. The degree of overlap between the bags and loops, and the proximity of their depth medians is reflected in the results of BEST tests comparing $\delta^{13}C_{coll}$ and $\delta^{15}N_{coll}$ values between the tissues which found
that they were very similar, with the starkest difference being the standard deviation for dentine $\delta^{15}N_{coll}$ (Appendix D).

The isotopic niche for the Finglesham community in earlier life seen in dentine is far broader than that represented by bone, which is interesting, when considering the formation times for the tissues, and the fact that bone remodels. We may have expected the opposite since bone should reflect a larger time frame which could therefore have far more dietary variability. I believe this is due to the high degree of mobility seen in the population. Therefore, the dentine represents $C_3$ diets. Whilst similar to the adult diets seen in bone, it has a broader isotopic niche due to the variety of environments these tissues were formed in.

Figure 8-28 uses bone, dentine and enamel isotopic data to look at trophic position and tissue offsets/enrichment through the life course. The patterns seen here closely mirror those for the kingdom level above in Figure 8-19. There is remarkable consistency over the life course in $\delta^{13}C_{coll}$ values, with very little change seen in Figure 8-28 c), although the same graph shows there is more diversity in $\Delta^{15}N_{dentine-bone}$ in the population, which is as expected given the differences between the bag plots of bone and dentine discussed above. $\Delta^{13}C_{carb-dentine}$ values shown in Figure 8-28 a), b) and d) are similar to those for the kingdom, however there are fewer individuals at Finglesham with low values, the majority sitting around 6-7‰. This means that most of the Finglesham subset have $\Delta^{13}C_{carb-dentine}$ values comparative to terrestrial and freshwater consumers on a scale from herbivory to omnivory, with six individuals whose values indicate a higher trophic level (Clementz et al., 2007, 2009; Clementz and Koch, 2001). Figure 8-28 a) demonstrates that these higher trophic positions (~5‰ or below) do not correlate directly to $\delta^{15}N_{coll}$ values, but what b) implies as it has done above, is that in $C_3$ diets, lower $\Delta^{13}C_{carb-dentine}$ values correlate with low $\delta^{13}C_{carb}$ values. This indicates that higher trophic levels in individuals may be due to freshwater resources rather than terrestrial or marine protein.

Figure 8-28 highlights the variability in childhood $\delta^{15}N_{coll}$ values compared to the signatures in bone, and the $C_3$ nature of diets of people at Finglesham. Very few individuals had protein-heavy diets, those which do are a minority, and this may be from freshwater resources. Since high $\delta^{15}N_{coll}$ values do not correspond with high
trophic levels at Finglesham despite the faunal evidence, as they do at the kingdom and England scale, we need concerted efforts to form more appropriate faunal baselines for sites, and consider what other aspects of agriculture and diet may be at play such as plant values (Hamerow et al., 2020).
Figure 8-28: Bag plots of Finglesham data a) $\Delta^{13}C_{\text{carbonate-dentine}}$ and $\delta^{15}N_{\text{dentine}}$ coll b) $\Delta^{13}C_{\text{carbonate-dentine}}$ and $\delta^{13}C_{\text{carb}}$ c) $\Delta^{13}C_{\text{dentine-bone}}$ and $\delta^{13}C_{\text{dentine}}$ d) $\delta^{13}C_{\text{dentine}}$ coll and $\Delta^{13}C_{\text{carb-dentine}}$. 
8.3.3 Sex

Figure 8-29: Violin plot of Finglesham human tooth enamel $\Delta^{18}O_{dW-MAP}$ (Chenery) values coloured by osteological sex, females n=16, males n=24.

Given the stark differences in height at Finglesham between females and males, I wanted to test if there were any mobility or dietary differences between the sexes on this smaller community scale.

Figure 8-29 compares $\Delta^{18}O_{dW-MAP}$ values between females and males, and, whilst bimodality is found in both groups, it is more evenly split in females who also have the highest values for the site. Both groups are skewed towards negative values and males have the lowest $\Delta^{18}O_{dW-MAP}$ values for the subsample. A BEST test showed no difference between the groups, however since this is largely based on means, it is perhaps not the best measure of the differences seen above in Figure 8-29 (see Appendix D). With a greater sample size from both sexes across the cemetery this picture could change but it does show that there was a large portion of the population with “non-local” signatures in both sexes. Given the diachronic changes above, perhaps marriage practices changed through time, or there were more local women and a gender imbalance during the seventh century in the cemetery, with males being buried elsewhere. This issue of a lack of male burials dated to later phases is a well-known problem in Early Medieval cemeteries, with a tendency to date “male” grave
goods such as weapons as significantly earlier than “female” dress accessories which show more stylistic changes through time (Bayliss et al., 2013; Brownlee, 2019).

Finglesham could therefore represent a largely immigrant population with incomers of both sexes, who may have practiced exogamy later in time with a mixture of “local” and “non-local” females and males present; however a larger sample size from both sexes and better dates for male graves in particular would be needed to confirm this. Do these sex-based differences in height and \( \Delta^{18}O_{dw-MAP} \) values bear out in diet? Are these differences in height due to nutrition more so than genetics, given that many females had similar childhood origins to the males?

Figure 8-30: Bag plot of female versus male bone \( \delta^{13}C_{coll} \) and \( \delta^{15}N_{coll} \) values at Finglesham.
What Figure 8-30 and Figure 8-31 show is that there is an almost complete overlap in bone values between females and males, but this is not the case for dentine. Despite the high degree of overlap in bag plots between female and male bone $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}_{\text{coll}}$ values, the inner bags are very different in shape. Diet in childhood, represented by dentine, is where the real differences lie with a high degree of overlap, but $\sim50\%$ of males having less negative $\delta^{13}\text{C}_{\text{coll}}$ and slightly lower $\delta^{15}\text{N}_{\text{coll}}$ values than females. Males occupy a larger isotopic niche in childhood in the Finglesham subset. Therefore, the question is, are these differences due to dietary or physiological differences? Or are they so small that they may be biochemically ephemeral? The relatively small differences suggest it might be the latter, as was suggested for dietary differences at an England-wide scale in Chapter 7.

8.3.4 Detecting deviants and community scale discussion
Some individuals from Finglesham have already been identified as outliers at the kingdom scale. Here I look at the cemetery in isolation to detect individuals who stand out within the community. Six individuals (graves 16, 106, 118, 133, 168 and 17) were removed by DDC due to having over 50% missing data, leaving 40 individuals suitable for DDC analysis. The results can be seen in Figure 8-32.
Six individuals who stand out with three or more deviating cells are summarised in Table 8-6. There is a mixture of females and males, and there are no clear trends in what variables they deviate in or their contextual data. Four of the individuals are coffin burials or possible coffin burials, and all bar one individual are aligned roughly W-E, however, as is clear in Figure 8-3, most burials are broadly on a W-E axis.

The two burials I would like to particularly highlight are grave 15 and grave 165, as they have the most deviating cells (four and five respectively) for the site. Both were also flagged by the kingdom level DDCs above. Grave 15 is flagged for number of grave goods (high), their δ13Ccoll values (low) and therefore also Δ13Cdentine-bone (high). Grave 165 was flagged for five variables (see above) and is a clear outlier for their community and the kingdom more generally in terms of their N-S orientation but also their diet, especially in childhood and the change between dentine and bone in terms of δ13Ccoll values. Both of these individuals, whilst not outliers in DDC for oxygen, have Δ18Odw-MAP values which suggest they are non-locals, so perhaps their deviance in diet is due to their foodways before coming to Kent. Using other methods, I would not have highlighted these individuals as particularly different from the rest of the group, so this certainly opens up avenues for further investigation.
Table 8-6: Individuals from Finglesham with three or more deviating cells identified by DDC in Figure 8-32.

It is interesting to note that the individuals who are outliers for oxygen (both $\delta^{18}O_{\text{phosphate}}$ and $\Delta^{18}O_{\text{dw-MAP}}$) in Figure 8-32 stand out as higher than predicted for both values, and all are female, bar one (gr 105). Their $\Delta^{18}O_{\text{dw-MAP}}$ values are all over +1‰, highlighting that the majority of the cemetery’s population with negative values is seen by the algorithm as the “norm”.

When this is compared with using the ±2‰ criteria for $\Delta^{18}O_{\text{dw-MAP}}$ values there are 19/40 individuals who fall outside the “local” range for Finglesham. Conversely these are mostly male burials (14/19), and the one outlier above +2‰ is female grave 21B. Five of these burials are flagged by DDC as outliers for a variety of variables, but not necessarily for oxygen isotope values. There do appear to be some key underlying differences in enamel $\delta^{18}O_{\text{phosphate}}$ and $\Delta^{18}O_{\text{dw-MAP}}$ values between female and male burials at Finglesham, and a tension between what is “normal” for the cemetery and kingdom in terms of mobility signatures versus the underlying “local” isoscapes. The DDC analyses have supported the fact that there does not seem to be any particular link between some aspects of burial practice, mobility or diet within this community.
and for the kingdom. Dietary outliers are rarely also mobility outliers, and neither are particularly linked to other non-isotopic variables.

Finglesham is a mostly migrant population where I can see change in diet from childhood to later in life, particularly in males. This suggests that these people spent quite some time in the region for their bone isotopic signatures to become more homogenised to reflect “Kentish” or perhaps Finglesham specific resources and foodways. Those who stand out in terms of bone values may be more recent incomers to the area.

Community summary:

- Sex based differences in diet and mobility are graphically visible on a cemetery-level scale, but dietary differences are so small they may be biochemically ephemeral.
- Finglesham is a community of predominantly “non-local” individuals.
- Diets in the community are more varied in earlier life and become more homogenous over time, suggesting diverse origins and long-term settlement in the area giving bone a “Finglesham” dietary signature.

8.4 Conclusions

This chapter has demonstrated the usefulness of analysing smaller regional/kingdom and site-specific isotope studies within a broader context. Moreover, it has shown that smaller polities and communities do sometimes deviate from the larger-scale isotopic patterns. For instance, dietary change over the life course and sex-based differences in mobility are more visible at Finglesham but not as clear at larger scales.

I have shown here that Early Medieval Kent and East Sussex, and the community buried at Finglesham within that, were from a diverse range of origins, and that migration to the area was likely continuous throughout the first millennium AD. Migrants could have come from areas of the Mediterranean up to northern parts of Scandinavia, with brewing and stewing also a potential factor for some individuals. This diversity in origins does not appear to correlate with any particular number or style of grave goods. The debated expressions and changes in “ethnic” identities
theoretically signalled by certain objects like brooches have far more complex cultural meanings and processes of construction behind them and are not closely associated with individuals with any particular isotopic signatures.

However, dietary change over the life course from diverse childhood diets to more homogeneous bone isotopic signatures, may be reflective of dietary syncretism or acculturation whilst in Kent and East Sussex, using local resources rather than importing foodways.

Furthermore there is subtle evidence for dietary change which may be linked to early Christian dietary practices being adopted in Kent as per the laws of Wihtred (Whitelock, 1994). This is reflected in the isotope values of all three tissues and suggests it began with increased freshwater resource consumption and a reduction in terrestrial animal protein before the adoption of the dietary changes seen by Knapp and others in the late seventh and eighth centuries of more fowl and marine fish in the zooarchaeological assemblages (Knapp, 2018; Thomas, 2010). Currently we have no human isotopic evidence for this later dietary shift due to a paucity of isotopic data from eighth century and later burials in Kent and East Sussex, making the zooarchaeological evidence and human isotopic record hard to align yet again.
9 Conclusions: Early Medieval Transitions – Diet, Mobility and Culture

This final chapter brings together the various aspects of the isotopic data explored in the previous chapters and considers them thematically to contextualise them within everyday life in Early Medieval England. I began this thesis with a quote from Jean Anthelme Brillat-Savarin - “Tell me what you eat, and I will tell you what you are”. Here I ask this of the isotopic signatures in these long-dead individuals, emphasising the who rather than the what. What did they eat and drink, where did they come from, but most of all, what can this tell me about who they were? This large multi-tissue, multi-isotope and multi-proxy study of socio-environmental transitions has allowed for new insights into life during the first millennium AD. I return to the concept of isotopic signatures as biological “memories” and imprints of the lives lived, food consumed, and environments inhabited by people in the past.

In this chapter I will summarise and discuss my major findings thematically, beginning with climate and environment, then changing foodways and migration before integrating these strands to (re)imagine life and identities in post-Roman to Anglo-Norman England. I end with some directions for future research and my key findings.

9.1 Climate and environment
A core theme of this thesis has been climate and the environment – how they impacted on human isotopic variation and how people interacted with and adapted to their environs in the Early Medieval period. I have sought to disentangle, at least in part, human actions and environmental signatures.

An exciting aspect to this work has been the visibility of major climate events in human enamel δ¹⁸O values. The LALIA and MWP climatic events are attested in contemporary sources as well as ice core sequences and dendrochronological records (Büntgen et al., 2016, 2017; Lamb, 1965; Mann et al., 2009; McCormick et al., 2012; Oliva et al., 2018). Only one study really considers these events and their impacts on the human isotopic record in the Middle Ages (Chambers, 2006). Whilst at present it
is hard to fully disentangle these climatic events, migration and culturally mediated fractionation without clear offsets and good chronological resolution from radiocarbon dates, my work begins to show how significant these events were to impact contemporary drinking water values alongside their other known socio-economic effects.

What I have shown in Chapters 5 through 8 is differential resource availability across regions due to climatic and environmental zones. This is true across western Europe but also within England. Whilst there are clearly environmental constraints on access to certain resources, some of this regional variation in isotopic signatures is due to human decisions and actions around food and drink. It has long been perplexing to archaeologists why, after the Mesolithic, most of Europe did not exploit marine resources for food to any large degree until the Roman period (Reynolds, 2015: 41–42). I do not offer any answers as to why, but, as others have mused, it is likely a complex mixture of ecology (for instance reduction in salinity in oceans due to warming events and ice melt, unfavourable ocean currents, etc.), cost-benefit analysis and perhaps even cultural taboos (Barrett, 2016; Reynolds, 2015). My analyses have shown that, at least in some parts of Early Medieval Europe, marine resources were a part of the diet (i.e. parts of the Mediterranean, the Orkneys and parts of Scandinavia), however they were not widely adopted elsewhere until after the eleventh or even twelfth century. However, I have found evidence for freshwater fish consumption in England where we previously were missing the human stable isotope evidence for this to any large degree, but this is not consistent throughout the whole period nor across all regions within England.

So, despite theoretically equal access to certain resources across Europe, the regional differences must also partly be due to human actions around food, its production and consumption which leads me onto my next section – changing foodways.

9.2 Changing foodways

Food and foodways in Early Medieval England (and Europe) were never static, if only due to seasonality of produce, so it should be no surprise that I have found such variation both geographically and diachronically in this thesis. My work here
supports the array of foods and drinks which Banham, Faith and Hagen describe in so far as they are plants and animals which are a part of C3 ecosystems (Banham, 2004; Banham and Faith, 2014a; Hagen, 2006). Foodways are extremely similar between England, the Irish Sea Region, the Jutland peninsula, Frisia, Saxony, Normandy/Neustria and Austrasia and Burgundy which fits well with the evidence for mobility and trade between these regions. Diets remain very similar through the life course for most of the population, however this could be different at smaller scales as shown at Finglesham.

Despite the zooarchaeological evidence of increased marine fishing around 1000AD, I have no clear isotopic evidence from human tissues in England that show diachronic changes in diet which are linked to marine resources (Barrett, 2016; Barrett et al., 2004a; Knapp, 2018; Müldner, 2016; Orton et al., 2017; Reynolds, 2015). However, the combination of several tissues within their environmental context has allowed me to identify freshwater fish consumption which is particularly clear from the seventh century onwards. This is consistent with the introduction of Christianity and dietary laws like those of Wihtred of Kent, and zooarchaeological assemblages such as those found in London and Lyminge (Barrett et al., 2004a; Knapp, 2018; Müldner, 2016; Orton et al., 2017; Reynolds, 2015). The marine FEH in England may be elusive in this dataset due to the small sample sizes from the mid-eleventh century onwards in England, giving the impression of a potential lag in isotopic signatures for marine resource consumption post-1000 AD. The analysis of more skeletons from the tenth century through to the fourteenth are needed to assess the uptake and spread of the FEH spatially and chronologically in England. However for the earlier converts freshwater resources and domestic fowl appear to have filled the requirements of orthopraxy in the meantime, with the impact of the FEH isotopically clear by the fourteenth century where more isotopic data are available (Hull, 2007; Knapp, 2018; Müldner, 2016; Müldner and Richards, 2007; Reynolds, 2015).

From approximately the eighth century onwards there are major shifts in human isotopic patterns. We get increasing $\Delta^{18}O_{	ext{dwi-MAP}}$ values, $^{15}$N enrichment with unexpected and complex apatite-collagen spacing (possibly indicating lower trophic levels but nitrogen enrichment due to changes in crop isotopes, or complex routing of lipids versus other dietary input or likely a mixture thereof), and relatively stable
\[ \delta^{13}C_{coll} \] bone values compared with earlier centuries. These shifts appear to be in line with not only the adoption of Christian foodways but they also align with the “agricultural revolution” of the eighth/ninth century and increased consumption and production of ale – in short, with the rise of settlement centralisation and urbanisation (Behre, 1999; Duby, 1997; Dyer et al., 2018; Hamerow et al., 2020; Hornsey, 2003: 233–259; Leggett, 2016; Unger, 2013: 22–52).

### 9.3 Migration

I set out to test three major migration events to England during the Early Middle Ages – the “Adventus Saxonum”, the Scandinavian settlements during the “Viking Age” and the Norman Conquest. Not only does the isotopic evidence support the first two events, but it shows that there was consistent migration from the end of the Roman period to at least the first half of the eleventh century. I have shown that migrants came to England from far further afield than the traditional narratives suggest, although we have to consider if the evidence that suggests that some of these people may be from the Mediterranean may instead be the result of “brewing and stewing”.

There is support for gendered aspects to these migration events; at a large-scale women, men and children from a variety of regions moved to and died in England, and these patterns varied through time. For the case studies of Kent and Finglesham I have shown that there may be more localised evidence for more male incomers who marry local women, but additional data is needed to investigate this further.

I have tried to analyse the data in a way that is sensitive to inter-regional variability in terms of potentially differential scales of immigration from the continent as per the call from Hamerow (1997). It is indeed hard to reconcile all of the lines of evidence and the opposing archaeo-historical paradigms of the past. However, my results clearly refute the elite replacement and ethnic-separation models proposed by Higham, Härke and Thomas amongst others (Härke, 2003, 2011, 2012; Higham, 2004; Pattison, 2008; Thomas et al., 2006, 2008). Instead, my results support the three general conclusions of Schiffels and Sayer (2017) – firstly that Early Medieval communities in England were of mixed isotopic origins (for them ancestry), secondly there are no clear links between grave goods and isotopic (or in their case genetic).
signatures, and thirdly there is no obvious delineations within most cemeteries between “locals” and “non-locals”. However as my isotopic dataset has better chronological coverage than Schiffels and Sayer’s small aDNA study, I have been able to investigate the Scandinavian and Norman migration events where geneticists usually find separating these events too difficult (Leslie et al., 2015; Martiniano et al., 2016; Schiffels et al., 2016; Schiffels and Sayer, 2017; Thomas et al., 2006; Winney et al., 2012).

Moreover, this high degree of mobility and migration seen in England is evident across Early Medieval Europe. My hierarchical clustering analyses and cross-regional comparisons suggest that cemeteries in most regions have “non-locals” in their ranks who were more or less integrated into these communities, at least in death. So, it is well and truly time for a paradigm-shift in the study of Early Medieval migrations, moving beyond elite-replacement and mass migration models to one of continual movement and cross-cultural contact.

9.4 (Re)Imagining everyday life in Early Medieval England

The richness of the isotopic data and the caution that is needed to analyse it often removes the personal aspect of the lived experiences which resulted in these chemical “memories” in skeletal tissues. What this thesis is centred around is daily life and identity, and what these isotopic “memories” of past lives can add to our understanding of life in Early Medieval England from the fifth to the eleventh century AD.

When I consider the isotopic data alongside the archaeological and historical evidence what I have found is a society whose identities on both individual and group levels are not constructed purely on the basis of kinship or homeland origins, but instead a more complex mixture of experiences and cross-cultural interaction, and these identities likely changed through life and through time. Identity here is taken as groupism centred around communities based on foodways and shared burial grounds and customs (Ayala et al., 2008; Bisogni et al., 2002; Brubaker, 2002; Fischler, 1988; Johnston and Longhurst, 2012; Kus, 2013; Reddy and van Dam, 2020; Ruiz et al., 2019; Sayer, 2010). Anthropological and sociological studies have shown how
important foodways are to migrants and identity – they keep homeland traditions alive, whilst also facilitating acculturation and integration in new communities (Ayala et al., 2008; Bisogni et al., 2002; Johnston and Longhurst, 2012; Parasecoli, 2014; Weller and Turkon, 2015). Food is central to group belonging, especially in rural communities, and helps blur cultural boundaries in multi-origin/multi-cultural societies (D'Sylva and Beagan, 2011; Fischler, 1988; Hage, 1997; Johnston and Longhurst, 2012; Reddy and van Dam, 2020; Ruiz et al., 2019). People in Early Medieval Europe clearly had more flexible concepts of identity than archaeologists are often willing to allow. I see this high level of mobility as less of an Early Medieval “identity crisis” or archaeology of “disruption” than one of constant adaptability (Baker and Tsuda, 2015; Hamerow, 1997; Hills, 2015). Communities buried their dead, regardless of where they grew up or who they were directly related to, alongside people they knew and ate with. In Kent for instance, the diversity of childhood diets almost vanishes by the time these people end up in the cemetery, and it seems to me these communities likely forged and re-enforced ties and identities through foodways, especially feasting and fasting, making their adult diets and identities far more interwoven. Meals in Early Medieval England were invariably communal in consumption, but also in production and heavily laden with meaning, bringing families and communities together (Effros, 2002; Frantzen, 2014: 9–82, 246–258; Hagen, 2006: 409–424; Jones, 2007; Lee, 2013; Stafford, 1980).

These cosmopolitan communities also changed their agricultural strategies and settlement patterns throughout the period. Diachronic changes in consumption seem to occur from the eighth century onwards. These changes could be due to migration, trade, Christian orthopraxy sweeping through Europe, or the need to alter agricultural regimes to feed increasingly urbanising populations (or a combination thereof). Unger (2013) sees clear links between brewing, cereal agriculture and urbanisation, and these forces seem to certainly be playing a role in the isotopic shifts I am seeing in these communities. This all supports the idea of population increase with the agricultural revolution, alongside Christian calendars adding to changing foodways in the period. Day-to-day, people were eating low-protein diets, full of cereals (whether in bread, ale or another form) which were being grown in innovative ways, supplemented, for what may be the first time, by aquatic resources.
as per Christian orthopraxy, which altered their isotopic “memories” as compared to their forebears.

From the fifth to the eleventh century, Europe saw many major socio-environmental transitions. Mobility, changes in foodways, material culture and identities are all symptomatic of people adapting in a very fluid manner to climatic as well as religious and economic shifts. Identities tied to food and other aspects of culture were mutable in the Early Middle Ages and changed like most aspects of society. The diachronic shifts I have described here align with many other changes we see during this period (LALIA, Christianisation, the Agricultural revolution...), and they reflect changing worldviews more than anything else.

9.5 Avenues for future research
Throughout the preceding chapters I have proposed avenues for future research where appropriate. Here I summarise some key areas which would benefit from further analyses and research. These can be broadly grouped into expanding the human isotopic datasets, isoscapes and baselines, modelling and other strands of biomolecular research.

9.5.1 Expanding human isotopic datasets
In terms of expanding the human isotopic datasets there is much that can be done to build upon the work here. First and foremost, isotopic analyses of more burials from the eighth century onwards are sorely needed, alongside better radiocarbon dating of these cemeteries to better understand diachronic changes in Early Medieval communities. It is clear from my work here that there are significant changes in human isotopic patterning from the seventh century onwards, and, if we are to better understand these changes and separate out the impacts of Christianisation, migration, climate change, the FEH and other factors, filling in the gaps in the burial and isotopic record from the eighth to the twelfth century and beyond is necessary.

I would also like to expand the isotopic work being done on Early Medieval communities elsewhere in Europe particularly in the Merovingian/Carolingian areas and around the Irish Sea where there are relatively fewer cemeteries and burials
analysed, but where we suspect there is a lot of cross-cultural contact and long-distance migrations (Hemer et al., 2013, 2014, 2017; Knudson et al., 2012; McManus et al., 2013; Nicolay, 2017; Ryan et al., 2018; Schuh and Makarewicz, 2016; Vytlačil et al., 2018).

Ideally more individuals would also have $^{87/86}$Sr and $\delta^{13}$C$_{carb}$ data from tooth enamel to give more robust multi-isotope datasets for provenancing models and understanding whole diet (and therefore looking at freshwater vs. marine consumption). Similarly, more work needs to be done across Europe for dentine $\delta^{13}$C$_{coll}$ and $\delta^{15}$N$_{coll}$ as there are so few studies it is hard to conclude much about Early Medieval childhood diet beyond the few studies in England.

Adding sulphur to the toolkit of these studies would be useful for understanding freshwater resource exploitation as well as another proxy for migration studies (Nehlich, 2015; Nehlich and Richards, 2009; Privat et al., 2007; Richards et al., 2001, 2003). This could be easily achieved using already extracted bone and dentine collagen although requires different technical specifications than were available to me at the Dorothy Garrod lab for this project.

9.5.2 Isoscapes and baselines
Isoscape modelling and baselines have come a long way but there are still large gaps in our understanding. My interpretations have been very limited here due to a lack of resolution or anachronistic data for climatic and geological isoscapes in certain parts of Europe, however new research is emerging to address this (Bataille et al., 2018, 2020; Kootker et al., 2016; Reynard et al., 2020; Willmes et al., 2018).

However, a lack of good baselines for dietary studies is a major problem throughout archaeological IA studies. Future research should put a greater emphasis on locating and analysing a wide range of fauna and botanical remains, to better capture the underlying environmental variation in the food chain “from the horse’s mouth” so to speak (Bownes et al., 2018; Casey and Post, 2011).
9.5.3 Modelling

Given the success of my EDA and UML approaches to the data in this thesis, I would like to build upon this by using more complex models. Specifically, I want to better integrate the archaeological data where possible, using a hierarchical-Bayesian-framework to perform mixed-effects modelling and predictive modelling using Random Forest analysis (Basu et al., 2018; Billheimer, 2019; Hadfield, 2010; Oczkowski et al., 2020; Verhagen and Whitley, 2012; Zhu and Sealy, 2019). Mixed models deal with “messy” data (i.e. the nested and unbalanced structures in this thesis with missing data) and can handle variables being covariate, to disentangle the degree of impact each variable has on the outcome (i.e. isotopic values). Random Forest analysis would allow me to create predictive models for assigning archaeological humans to groups (areas of origin) based on their isotopic, osteological and burial data. I would also like to run some Bayesian stable isotope mixing models (SIMMs) for sites and regions with good faunal baselines to try and assess human diets using these frameworks (Lewis and Sealy, 2018; Moore and Semmens, 2008; Parnell et al., 2013; Semmens et al., 2009; Stock et al., 2018; Stock and Semmens, 2016; Ward et al., 2010).

9.5.4 Other biomolecular research

As mentioned in Chapter 1, studies using aDNA, residue analysis and proteomics (especially on dental calculus) in Early Medieval settings have so far been extremely limited (Baeten et al., 2013; Dunne et al., 2019, 2020; Jersie-Christensen et al., 2018; Keller et al., 2019; Martiniano et al., 2016; Radini et al., 2019; Schiffels et al., 2016; Schiffels and Sayer, 2017). However, these techniques are yielding important insights, especially when combined with other aspects of archaeological, documental and biomolecular evidence. I hope that a continued, considered and ethical use of these techniques will greatly add to our knowledge of mobility, diet, health and identity in the Early Middle Ages.

9.6 Conclusion

I have used multi-tissue, multi-isotope and multi-proxy data to analyse the lifeways of people in Early Medieval England within a European context. I have shown throughout this thesis the high levels of variability and dynamism within Early
Medieval communities and their roles in socio-environmental transitions across the first millennium AD.

One major finding is the high degree of regional isotopic variation across Europe and within England during the Early Middle Ages found in all three tissues – enamel, dentine and bone. This is not unsurprising given the large geographical areas, diversity of environments and cultures these meta-analyses cover; however, this is the first time they have been characterised specifically for the Early Middle Ages at such a large scale. This allows us to better provenance people based on this diversity and see cross-cultural contact. It also highlights the impact of climate change (LALIA and MWP) on human δ¹⁸O values, showing the widespread and relatively rapid impact these events had on climate and on drinking water sources.

Diachronic change both in diets and in mobility patterns reflect the highly dynamic and far from insular position of England within its European context. They reflect not just shifts in economics and agricultural practice but changing worldviews. The data are extremely heterogeneous suggesting isotopic baselines were far more diverse and intra-population variation much larger than current models allow. Even when taking into account the variation and uncertainty introduced by "brewing and stewing", inter-laboratory differences and analytical error the heterogeneity of the dataset is still prominent. It speaks not just to natural or scientific variation but to the complexity of human action in the past, what was probably continual and large-scale migration and changing foodways in England from the end of the Roman period to the turn of the first millennium AD.

Isotopic analyses when combined with other lines of evidence show here that identity construction in Early Medieval communities was highly complex, and there is no clear link between isotopic patterns, genetics and grave goods usually seen as “ethnic” signifiers. These were multi-origin communities in continual cross-cultural contact who were tied into broad networks which influenced the changes we see in thought, consumption and material culture throughout the period.
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